

**Abstract**—Rockfish species are notoriously difficult to sample with multi-species bottom trawl survey methods. Typically, biomass estimates have high coefficients of variation and can fluctuate outside the bounds of biological reality from year to year. This variation may be due in part to their patchy distribution related to very specific habitat preferences. We successfully modeled the distribution of five commercially important and abundant rockfish species. A two-stage modeling method (modeling both presence-absence and abundance) and a collection of important habitat variables were used to predict bottom trawl survey catch per unit of effort. The resulting models explained between 22% and 66% of the variation in rockfish distribution. The models were largely driven by depth, local slope, bottom temperature, abundance of coral and sponge, and measures of water column productivity (i.e., phytoplankton and zooplankton). A year-effect in the models was back-transformed and used as an index of the time series of abundance. The abundance index trajectories of three of five species were similar to the existing estimates of their biomass. In the majority of cases the habitat-based indices exhibited less interannual variability and similar precision when compared with stratified survey-based biomass estimates. These indices may provide for stock assessment models a more stable alternative to current biomass estimates produced by the multispecies bottom trawl survey in the Gulf of Alaska.

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## Comparison of habitat-based indices of abundance with fishery-independent biomass estimates from bottom trawl surveys

**Christopher N. Rooper (contact author)**

**Michael H. Martin**

Email address for contact author: Chris.Rooper@noaa.gov

Alaska Fisheries Science Center  
National Marine Fisheries Service  
National Oceanic and Atmospheric Administration  
7600 Sand Point Way NE  
Seattle, Washington 98115

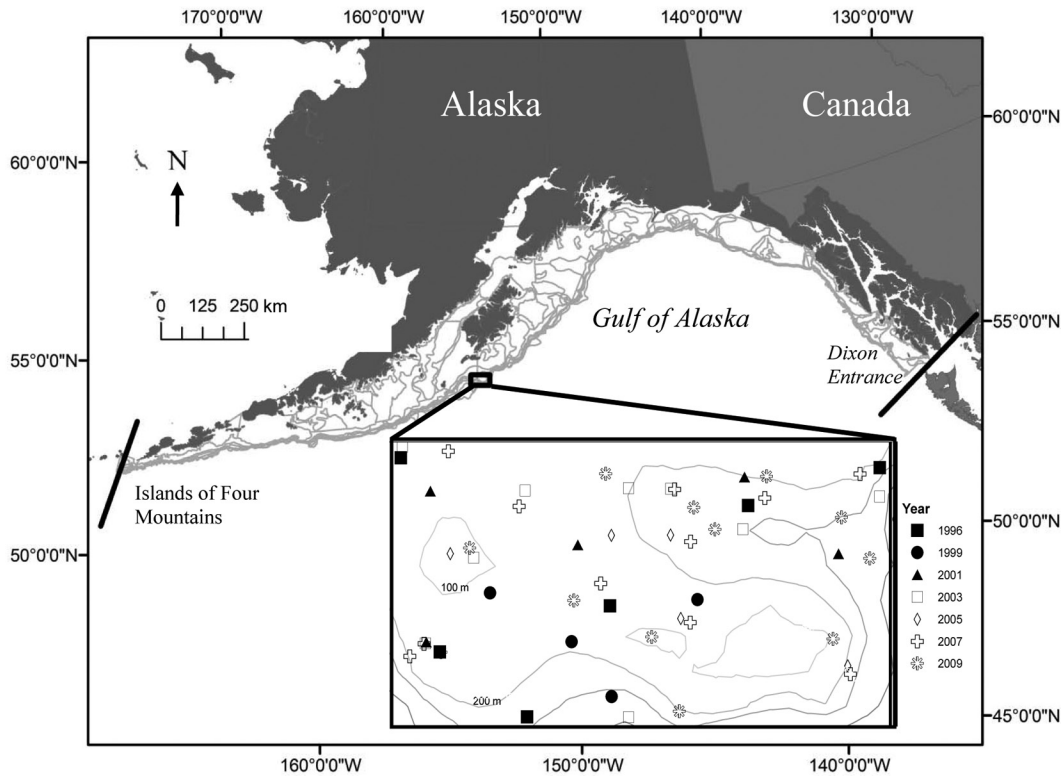
Abundance indices from fishery-independent surveys of marine fish species are widely used to determine trends in species abundance. Most broad-scale surveys are designed to estimate abundance for multiple species and have been an important data source for producing fisheries stock assessments for commercially exploited species. A problem in estimating the biomass for an individual species in a multispecies survey occurs for species not evenly distributed over the survey area or when the sample allocation (in terms of either locations or number of samples) is not ideal for estimating the abundance of the species in question. These two problems affect fish that have affinities for specific habitat types so that the availability of the fish to the survey may change with habitat type (Cordue, 2007). Additionally, this situation is especially true for bottom trawl surveys where all habitat types may not be sampled equally with the survey gear (Zimmermann, 2003).

One solution may be habitat-based surveys of abundance for fish species with strong habitat affinities. For these species, habitat-based abundance indices have a clear advantage over other methods because they incorporate prior knowledge of fish distributions, such as habitat-based surveys for cowcod (*Sebastes levis*) and yelloweye rockfish (*S. ruberrimus*) (O'Connell and Carlile, 1993; Yoklavich et al., 2007). These surveys produce fishery independent estimates of biomass that are based

on applying the mean density within a habitat to the total area that the habitat comprises in the ecosystem.

Rockfish are difficult species to assess in Alaska and along the U.S. west coast owing to their patchy distribution and strong habitat affinities (Clausen and Heifetz, 2002; Rooper et al., 2007). Stratified, random bottom trawl surveys are commonly used for these species, and typically catch-per-unit-of-effort data for each species are expanded across entire strata to estimate a total biomass for a species (e.g., Wakabayashi et al., 1985). Strata are typically defined as regions of similar bathymetry or geographical features. For example, in the Gulf of Alaska, three types of strata have generally been defined: the continental shelf, continental slope, and gullies intruding on the continental shelf.

Trawl surveys generally produce highly variable and unstable biomass estimates for rockfish species. Part of this is due to the multispecies nature of the sample allocation and stratification schemes, which lead to inter-survey differences in the amount and types of habitat sampled from year to year. For example, an area commonly referred to as the "Snakehead" has historically been an important area for the commercial rockfish fishery in the Gulf of Alaska, producing a substantial portion of the rockfish catch in some years (Clausen and Heifetz, 2002). The number of stations randomly selected in the bottom trawl survey at the "Snakehead" has



**Figure 1**

Map of the northern Gulf of Alaska showing stratum boundaries (gray lines) for the Gulf of Alaska bottom trawl survey. The survey is conducted at stratified random stations in the area bounded by lines at the Islands of Four Mountains (170°W longitude, 53°N latitude) and Dixon Entrance (133°W longitude, 55°N latitude). The inset shows the station pattern for each survey year since 1996 for the “Snakehead,” an area historically important for the commercial rockfish fishery.

ranged from a low of four in 1996 to 12 in 2009 (Fig. 1). Thus, habitats are not sampled in proportion to their importance to rockfish in some years. The specific pat-

terns in rockfish habitat use can have a significant effect on the accuracy and precision of bottom trawl survey biomass estimates (Cordue, 2007). In addition, survey designs may change from year to year, such as has occurred with the Alaska Fisheries Science Center’s Gulf of Alaska bottom trawl survey, where interannual variability in agency funding has resulted in dissimilar spatial and depth coverage during some survey years (Table 1). Habitat and survey-design effects are often observed as large coefficients of variation around biomass estimates for rockfish species and as biologically unlikely changes in biomass estimates from year to year. Thus, there is a serious need for the inclusion of habitat information into methods for estimating annual indices of abundance for rockfish species.

The objective of this project was to develop a generic framework to create a habitat-based annual abundance index for rockfish species in Alaska. First, a model of catch per unit of effort in relation to habitat variables was developed that also contained an index of the year effect on abundance. The residuals from this model were then examined to determine whether spatial structure was present. We compared the model-based annual abundance index to the swept-area biomass estimates, where both were derived from the

**Table 1**

Number of Gulf of Alaska bottom trawl survey hauls included in the modeling analysis of rockfish abundance for each year that a survey was conducted. Also reported are the minimum and maximum depths of bottom trawl survey tows in each year of the survey.

Year	No. of hauls	Minimum depth (m)	Maximum depth (m)
1996	605	31	479
1999	665	23	946
2001 <sup>1</sup>	376	24	448
2003	668	31	667
2005	690	23	882
2007	660	31	903
2009	811	21	984
Total	4475		

<sup>1</sup> Only the western Gulf of Alaska was surveyed during this year.

bottom trawl survey data. This method was applied to eight species of rockfish in Alaska for which the data from the current bottom trawl survey produce a range of coefficients of variation around the mean annual abundance estimate.

## Materials and methods

The data used for these analyses were collected during bottom trawl surveys of the Gulf of Alaska (GOA). The National Marine Fisheries Service (NMFS), Alaska Fisheries Science Center (AFSC), has conducted standard bottom trawl surveys on the continental shelf and slope since 1980 (von Szalay et al., 2010). The Gulf of Alaska bottom trawl survey is conducted from the Islands of Four Mountains (170°W) to Dixon Entrance (133°W) (Fig. 1). Surveys were conducted triennially between 1993 and 2000 and biennially thereafter; for our analysis, AFSC bottom trawl data from 1996 to 2009 were used (Table 1). The 1996 bottom trawl survey was the first for which accurate temperature at depth data were available for calculating water column properties used in the modeling. In the GOA bottom trawl survey, a poly Nor'Eastern high-opening bottom trawl with a 24.2-m roller gear footrope constructed with 36-cm rubber bobbins separated by 10-cm rubber disks is used (Stauffer, 2004). Trawl hauls were conducted at a speed of 5.6 km/h (3 knots) for 15 or 30 minutes. Bottom contact and net dimensions were recorded throughout each trawl haul with net mensuration equipment. For these analyses, records were used only if trawl performance was satisfactory and if the distance fished, geographic position, average depth, and water temperature profile were recorded. Trawl hauls were deemed satisfactory if the net opening was within a predetermined normal range, the roller gear maintained contact with the seafloor, and the net suffered little or no damage during the tow. Data from a total of 4475 bottom trawl hauls were used (Table 1).

All fish captured during a survey tow were sorted to species, counted, measured for total or fork length, and the total weight of each species in the catch was determined. For large catches, the total catch was weighed and subsampled for count and length data. Catch per unit of effort (CPUE, no. of fish/ha) for all fish species was calculated by using the area swept computed from the net width at the wingtips for each tow multiplied by the distance towed recorded with global positioning systems. Catch data were transformed by using the natural log ( $CPUE + \text{constant}$ ) before analyses, hereafter shortened to LCPUE. Three constants were examined: a constant of 1, a constant of 10% of the mean CPUE value, and a constant of 0.5 times the minimum observed CPUE value greater than zero. In the case of shortspine thornyhead (*Sebastolobus alascanus*), the constant of 1 best fit the assumption of normally distributed errors. For the other species, a constant of 0.5 multiplied by the minimum observed CPUE value greater than zero was used.

## Habitat modeling

Ecological theory predicts that the abundance of a population should be related to the availability of resources in the organism's habitat (Hutchinson, 1957). These relationships between habitat and abundance can be easily modeled by using generalized linear models or generalized additive models, but these methods may not be appropriate for nonlinear responses (generalized linear models) or may overfit the data (generalized additive models), and therefore they may not be robust for prediction when applied outside the data set on which they are parameterized (Venables and Ripley, 2002). In practice and theory, the relationships between animal abundance and habitat have typically been described by linear relationships, density-dependent functions, and dome-shaped curves (May, 1973; Murawski and Finn, 1988; Friedlander and Parrish, 1998; Iles and Beverton, 2000). Our approach was to parameterize these relationships to provide a biologically meaningful model of the animal's relationship with its habitat and thereby give robust predictions (Rooper et al., 2005; Rooper and Martin, 2009).

Habitat models for each of eight species of rockfish (Table 2) were determined using the two-stage modeling methodology of Rooper and Martin (2009). Pacific ocean perch CPUE (*S. alutus*) was divided into a juvenile component (<250 mm fork length) and an adult component (> 250 mm fork length) because individuals at these two life history stages are known to prefer different habitats (Carlson and Straty, 1981; Rooper et al., 2007; Rooper, 2008). Juvenile and adult Pacific ocean perch were then modeled separately. Recently, the rougheye rockfish (*S. aleutianus*) has been divided into two species: rougheye and blackspotted rockfishes (*S. melanostictus*; Orr and Hawkins, 2008). These two species are difficult to positively identify in the field and are still evaluated as a single species for stock assessment purposes; therefore, they were lumped as one species for this analysis.

Initially, the presence or absence (R) of each species in the trawl survey data was used to determine tows that were outside the natural range of the species. Data from the 1999, 2003, 2005, 2007, and 2009 bottom trawl surveys were used to determine the species range because these were the only years in which sampling was conducted at depths to at least 700 m and across the entire GOA region. Depth (D), temperature (T), and longitude (L) were the primary variables used to determine the range limits for each rockfish species. Continuous depth and temperature measurements were collected during each trawl haul with calibrated SeaBird (SBE-19 or SBE-39) microbathythermographs (Sea-Bird Electronics, Inc., Bellevue, WA) attached to the headrope of the net. Position data (latitude and longitude) were collected every second during each bottom trawl tow. The average bottom depth and bottom temperature and the longitude from the midpoint of each trawl haul were used to predict the presence or absence of the species. The Gulf of Alaska bottom trawl survey is conducted within the middle of the overall range (both from north

**Table 2**

Species of rockfish examined in the habitat modeling analysis of the Gulf of Alaska bottom trawl survey data and the portion of their distribution where they are commonly found according to Love et al. (2002).

Common name	Species name	Common distribution range
Dusky rockfish	<i>Sebastes variabilis</i>	Southeastern Alaska through Eastern Aleutian Islands
Sharpchin rockfish	<i>Sebastes zacentrus</i>	Southern California to Kodiak Island
Pacific ocean perch <sup>1</sup>	<i>Sebastes alutus</i>	Northern California through Aleutian Islands and Bering Sea
Rougheye and blackspotted rockfish	<i>Sebastes aleutianus</i> and <i>S. melanostictus</i>	Central Oregon through Aleutian Islands and Bering Sea
Harlequin rockfish	<i>Sebastes variegatus</i>	British Columbia through the Gulf of Alaska
Northern rockfish	<i>Sebastes polyspinis</i>	Central Gulf of Alaska through the Aleutian Islands and Bering Sea
Shortraker rockfish	<i>Sebastes borealis</i>	British Columbia through Aleutian Islands and Bering Sea
Shortspine thornyhead	<i>Sebastolobus alascanus</i>	California through Aleutian Islands and Bering Sea

<sup>1</sup> This species was divided into juvenile and adult catch components with each modeled separately.

to south and from west to east) for Pacific ocean perch, shortspine thornyhead, rougheye and blackspotted rockfish, and shortraker rockfish (*S. borealis*) (Table 2; Love et al., 2002); therefore it is unlikely that geographic position had a strong influence on the presence or absence of these species in this range. The longitude variable was therefore not used for these species.

The cumulative distribution function (CDF) of rockfish abundance was calculated over the range of depth, temperature, and longitude variables to determine the niche dimensions of each species. From the original 3394 trawl hauls from 1999, 2003, 2005, 2007, and 2009, replicate tows were chosen (with replacement) and the 5th and 95th percentiles of the cumulative distribution function were computed for each variable. This process was simulated 100 times for each of the variables (depth, temperature, and longitude). The average 5th and 95th percentiles were computed from the simulations for each variable, and the trawl haul tows occurring outside this range (below the 5th percentile or higher than the 95th percentile for depth, temperature, or longitude) were predicted to have occurred outside the niche of the rockfish species. Thus, no rockfish were predicted to occur at stations outside of the species niche ( $R=0$  in Eq. 1), whereas stations within the species depth, temperature, and longitudinal niches were predicted to have rockfish present ( $R=1$ ). For example, on average 90% of the juvenile Pacific ocean perch CPUE in the trawl hauls came from stations between 85 and 217 m depth, and therefore juvenile Pacific ocean perch were predicted to occur at stations within the depth range ( $R=1$ ) and predicted not to occur at stations shallower and deeper than these depths ( $R=0$ ). The 5th and 95th percentiles of the cumulative distribution were used to reduce spurious data (such as where depth, temperature, or species identification were recorded incorrectly) and

to reduce the effect of outlying catches that occurred at the extreme edges of the depth and temperature distributions of the species. There has been no indication of changes in the underlying depth and temperature niche dimensions of rockfish over time (NPFMC, 2009).

The second stage of the modeling was to develop a predictor of abundance for each rockfish species at stations where they were predicted to be present. Up to six variables were used to model rockfish abundance: depth and temperature, as well as habitat variables chosen for their potential importance to growth and survival. The suite of habitat variables for each species included an index of local bottom slope (S); the ratio of the thermocline depth to the bottom depth (TD); an index of predation refuge based on coral and sponge abundance (CS); and for shrimp-eating species, an index of prey abundance (P) (Table 3).

The index of local bottom slope was calculated for each trawl survey station by using bathymetry maps with depth contours in 100-m increments from 0 to 2000 m (derived from ETOPO2 gridded elevation data, <http://www.ngdc.noaa.gov/mgg/global/etopo2.html>). The bathymetry was kriged over the station grid for the Gulf of Alaska and the slope was calculated from this surface by using ArcGIS spatial analyst tools (ESRI, Redlands, CA). The local slope was extracted from this surface for a latitude and longitude pair at the midpoint of each bottom trawl haul.

Productivity in the water column is often related to water column stratification (Whitney et al., 2005; Strom et al., 2007). For example, where the water column is well-mixed (where there is a small temperature difference between surface and deeper water and a deep or absent thermocline), upwelling, wind, or tidal mixing may be occurring, indicating higher availability of nutrients for primary productivity in the area. Conversely

**Table 3**

Habitat variables (and abbreviations from the text) used in the habitat modeling analysis for rockfish species in the Gulf of Alaska. The units of each measurement and the definition of how the variable was acquired, the process the variable is meant to index, and the source of the data are also provided.

	Unit	Definition	Index	Data source
Shrimp abundance (P)	kg/ha	Shrimp (combined species) catch per unit of effort	Prey availability	Bottom trawl haul catch
Bottom temperature (T)	°C	Average bottom temperature		microbathy-thermograph
Bottom depth (D)	m	Average bottom depth		microbathy-thermograph
Local slope (S)	% change	Slope at each bottom trawl station		Kriged bathymetry maps
Coral and sponge abundance (CS)	log(kg/ha)	Combined catch per unit of effort of sponge and coral	Refuge from predation	Bottom trawl haul catch
Thermocline depth/bottom depth (TD)		Ratio of the thermocline depth to the bottom depth	Water column stratification	microbathy-thermograph

a shallow thermocline could indicate nutrient-limited growth. For this analysis the water column stratification was estimated by the ratio of the thermocline depth to the bottom depth (i.e., when the ratio=1, the entire water column was mixed and no thermocline was present). The depth of the thermocline was estimated algorithmically from data collected with the microbathy-thermograph (MBT) attached to the trawl headrope. Data representing less than 5 meters in depth were excluded. The temperatures as a function of depth were smoothed with a smooth spline implemented in R software (R Foundation for Statistical Computing, Vienna, Austria) and the rate of change in temperature per unit of depth was estimated by dividing the change in smoothed temperature by the change in depth for each successive MBT observation. The descent rate of the net slows as it approaches the bottom after the doors have reached the bottom, and this slow descent sometimes resulted in anomalous results as the changes in depth became quite small. Therefore, data where the rate of depth change fell below 0.12 m/s (almost exclusively after doors reached the bottom) were excluded from consideration. No thermocline estimation was attempted when the temperature difference between the maximum and minimum temperatures during the descent of the trawl net were less than 0.4°C and these areas were assumed to be well-mixed to the bottom. The resulting estimates were binned into 10 equal intervals between 5 meters and the maximum depth when the net reached the bottom. A mean of the rate of temperature change was estimated for each bin. Within the bin with the highest negative mean temperature change, the single depth observation associated with the highest negative temperature change was used as the estimate of thermocline depth.

Rocky, hard bottom substrates and benthic invertebrates are sources of refuge from predators and thus

are presumed to be important in determining survival. Hard seafloor in Alaska is often substrate for a combination of benthic invertebrates, including corals and sponges (Freese, 2001), and rockfishes are often associated with these invertebrates (Rooper and Boldt, 2005). The log-transformed CPUE of combined coral and sponge (coral and sponge abundance) was used as an index of the amount of potential refuge from predation at each trawl haul site in this analysis.

The final habitat variable used in this analysis was an index of prey availability for the species (shortspine thornyhead, rougheye and blackspotted rockfish, and shortraker rockfish) that consumed large or benthic prey (such as shrimp, squid, or myctophid fish). Shrimp of a number of taxa (Pandalidae, Crangonidae, etc.) are captured in bottom trawl hauls and the shrimp abundance (kg/ha) for each bottom trawl haul was used as an index of the amount of prey available at the trawl survey station for the shrimp-consuming species.

To model rockfish abundance, LCPUE was estimated as a function of six habitat variables: depth (D), temperature (T), thermocline depth to bottom depth ratio (TD), local bottom slope (S), coral and sponge abundance (CS), shrimp abundance (P), and a dummy variable indicating the year effect (Y):

$$LCPUE = R * \left[ \frac{f(D) + f(T) + f(S) + f(TD) + f(CS) + f(P) + Y + \epsilon}{f(CS) + f(P) + Y + \epsilon} \right], \quad (1)$$

where  $R$  = presence (1) or absence (0) in the analysis of niche dimensions (stage 1), and  $\epsilon$  is the error term.

As in Rooper and Martin (2009), the relationships between rockfish LCPUE and habitat variables were estimated with one of three equations. The most com-

plex equation (having the most parameters) had three parameters and represented the response of LCPUE as a symmetrical dome-shaped function of the habitat variables, so that

$$LCPUE_h = \alpha_h + \beta_h X_h + \phi_h X_h^2. \quad (2)$$

Here,  $X_h$  = habitat variable  $h$ ; and  $\alpha_h$ ,  $\beta_h$ , and  $\phi_h$  are parameters fitted to the data.

The second equation describes LCPUE as an exponential function of the habitat variables, so that

$$LCPUE_h = a_h X_h e^{-b_h X_h}. \quad (3)$$

In this case, only two parameters,  $a_h$  and  $b_h$ , are fitted. With the simplest equation (least parameters), the predicted rockfish abundance was computed as proportional to the habitat variables  $X_h$ , so that

$$LCPUE_h = c_h X_h, \quad (4)$$

where  $c_h$  = the only parameter fitted in the equation.

All components of LCPUE were combined before fitting the parameters. For example, the initial (full) model for the shortspine thornyhead analyses estimated 18 parameters plus one dummy parameter for each year, by using the 3-parameter equation (Eq. 2) for each of the six variables so that

$$\begin{aligned} LCPUE = & \alpha_D + \beta_D X_D + \phi_D X_D^2 + \alpha_T + \beta_T X_T + \phi_T X_T^2 + \\ & \alpha_{TD} + \beta_{TD} X_{TD} + \phi_{TD} X_{TD}^2 + \alpha_S + \beta_S X_S + \phi_S X_S^2 + \alpha_{CS} + \\ & \beta_{CS} X_{CS} + \phi_{CS} X_{CS}^2 + \alpha_P + \beta_P X_P + \phi_P X_P^2 + Y + \epsilon. \end{aligned} \quad (5)$$

All 18 parameters, plus the year effects, were fitted simultaneously.

Model parameters were estimated by minimizing the negative log-likelihood (Hilborn and Mangel, 1997), by using either a normal or a gamma distribution dependent on the characteristics of the model residuals. For Pacific ocean perch, shortspine thornyhead, short-raker rockfish, sharpchin rockfish, and roughey and blackspotted rockfish, species for which there were no major departures from normality, the normal distribution was used. In the cases of dusky rockfish, harlequin rockfish, and northern rockfish, a gamma distribution with shape=0.5 and scale=1 was used to fit the model parameters.

Models were reduced by sequentially removing one parameter for a variable (e.g., the depth relationship was changed from Eq. 2 to Eq. 3) and parameters were refitted. Next another parameter for that variable was removed (e.g., the depth relationship was changed from Eq. 3 to Eq. 4) and the model was refitted. This was repeated until the variable was no longer included in the equation (all parameters were removed). Then these steps were repeated for the next five variables. The models were compared by using the Akaike information

criterion (AIC) for non-nested models to determine the best fitting model:

$$AIC = 2L + 2p, \quad (8)$$

where  $p$  = the number of parameters in the model; and  $L$  = the sum of the negative log-likelihood of the model given the data (Akaike, 1992).

The best of this series of models was then evaluated against the full 18-parameter model. If there was a reduction in the AIC from the full model, the new model was kept as the best fitting model. Further parameter reductions were implemented by repeating the steps above and comparing the results to the best-fitting model from the previous series, until the reduction in the number of parameters or elimination of variables resulted in no reduction in the AIC score, and this final model was deemed best for the data set analyzed. The  $r^2$  (squared correlation coefficient) between the observed and predicted values was used to determine the percentage of variance in the LCPUE data set explained by the model.

To examine potential spatial correlation that was unrelated to habitat variables we analyzed the residuals for the best fitting model. The residuals from the best-fitting model were kriged across the geographic area of the survey by fitting a generalized least squares trend surface (Venables and Ripley, 2002) and assuming a spherical covariance function for a range of distances from 0.01° to 1° of latitude and longitude. To predict the values at each bottom trawl survey station, the trend surface value at each station was added back to the model prediction (Hengl et al., 2007). The correlation between the observed and predicted values (plus the kriged surface value) at the range of distances was used to determine the scale of spatial correlation. The values from the best-fitting surface (with the highest correlation coefficient) were then compared to the results without the addition of the trend surface to determine whether a significant amount of residual variance could be explained by spatial autocorrelation in the residuals.

## Abundance indices

The annual abundance index was estimated by the dummy variable for the year effect ( $Y$ ). Because this was the variable of interest in the modeling (i.e., producing a time series of annual abundance from the model), it was included in all of the models and not tested for significance with the AIC method above. Errors for all parameter estimates in the best-fitting model (including the year effect) were estimated by bootstrapping. The data were resampled 500 times with replacement, the form of the best-fitting model was refitted to the resampled data, and the parameters were recalculated for each bootstrap. Confidence intervals for the mean were estimated for each of the years from the bootstrap data. The year-effect estimate and confidence intervals were then back-transformed from  $\log(\text{CPUE})$  and the constant

**Table 4**

Correlations ( $r$ ) among habitat variables for the combined Gulf of Alaska (1996–2009) data sets based on 4475 bottom trawl hauls.

	Shrimp abundance	Bottom temperature	Bottom depth	Local slope	Coral and sponge abundance
Bottom temperature	-0.008				
Bottom depth	0.055	-0.372			
Local slope	-0.083	-0.219	0.545		
Coral and sponge abundance	-0.013	-0.061	0.035	0.125	
Thermocline depth/bottom depth	-0.125	0.140	-0.407	-0.212	0.068

was removed to produce a CPUE (in no. of rockfish/ha) for each year. In the case of Pacific ocean perch, back-transformed juvenile and adult CPUEs were summed to obtain an annual abundance estimate for that species.

Because the GOA bottom trawl survey is a stratified random survey, the comparable design-based CPUE estimates (kg/ha), as well as their variances, were calculated according to the formula of Wakabayashi et al. (1985). These CPUE estimates were calculated for each year of survey data and were expanded over the survey area to estimate the total biomass used in stock assessments in the GOA. These biomass estimates and their variances were compared to the model-derived abundance indices for each species by using linear regressions.

## Results

Cross correlations among variables used to predict rockfish presence, absence, and abundance were not large in most cases (Table 4). The strongest correlation was between the local slope and bottom depth variables and was probably indicative of larger slope values at and near the continental shelf break where depths increased. Bottom temperature and the thermocline-depth-to-bottom-depth ratio were also marginally correlated with bottom depth. The remaining variables were generally not strongly correlated ( $r^2 < 0.05$ ).

Models of rockfish distribution fitted very poorly ( $r^2 < 0.05$ ) for dusky rockfish (*S. variabilis*), northern rockfish (*S. polyspinis*), and harlequin rockfish (*S. variegatus*). The poorly fitted species appeared to be the result of a poor ability to predict presence, so that these species were not present at >80% of the trawl hauls where they were predicted to occur (Table 5). This finding may be a result of uneven sampling of their preferred habitat. For example, northern rockfish, dusky rockfish, and harlequin rockfish are all known to prefer rocky areas that are largely inaccessible to survey bottom trawl gear.

For the five remaining species, the method was reasonably accurate in predicting the presence or absence of a species at a trawl station (Table 5). Presence or absence for these five species was predicted correctly in

>60% of the bottom trawl hauls. For these species, the variance explained by abundance models ranged from an  $r^2 = 0.22$  for juvenile Pacific ocean perch LCPUE to an  $r^2 = 0.66$  for shortspine thornyhead (Table 6). Comparisons of the residuals from the models to the normal distribution indicated that the residual errors were similar to a normal distribution for these five species (Fig. 2).

Local slope was significant in the best-fitting models of shortspine thornyhead, shorttraker rockfish, rough-eye and blackspotted rockfish, sharpchin rockfish, and both juvenile and adult Pacific ocean perch, and it had considerable explanatory power for four of the six best-fitting models. Depth was also an important variable included in four of the six best-fitting models for these species. Coral and sponge abundance was significant in all the best-fitting models, although shortspine thornyhead LCPUE was negatively correlated with coral and sponge abundance (Fig. 3). Thermocline depth to bottom depth ratio was positively correlated with abundance of adult Pacific ocean perch and sharpchin rockfish LCPUE and was negatively correlated with juvenile Pacific ocean perch, shortspine thornyhead, and rough-eye and blackspotted rockfish LCPUE, and was insignificant in the shorttraker rockfish model. The effect of this variable was also relatively weak in most cases (Table 6). Shrimp abundance was included in the best-fitting models for those species that consume shrimp, albeit in a nonintuitive fashion for shorttraker and rough-eye and blackspotted rockfish (Fig. 3).

The spatial patterns in the residuals did not reveal significant spatial structure remaining in the data after the modeling was completed. The increase in the correlation coefficient was marginal (<4%) when the kriged surface values were added to the predicted values at each bottom trawl survey point. The spatial structuring was weak, indicating that high catches of most rockfish species were very patchy and that catches from the closest neighboring tows could be very different. The distances between stations at which the spatial autocorrelation in the data was maximized were small (ranging from 9 km for juvenile Pacific ocean perch to 33 km for rough-eye and blackspotted rockfish). Thus, the scale of the patchiness of the data was probably much less than could be captured by the bottom trawl data.

Table 5

The predicted and observed presence and absence of each rockfish species based on the niche prediction model for the 1996–2009 Gulf of Alaska bottom trawl survey data.

Species		Predicted absent	Predicted present
Dusky rockfish	Observed absent	2777	1293
( <i>Sebastes variabilis</i> )	Observed present	193	212
Harlequin rockfish	Observed absent	2878	1421
( <i>Sebastes variegatus</i> )	Observed present	62	114
Northern rockfish	Observed absent	3126	802
( <i>Sebastes polyspinis</i> )	Observed present	338	209
Juvenile Pacific ocean perch	Observed absent	2078	1566
( <i>Sebastes alutus</i> )	Observed present	183	648
Shortspine thornyhead	Observed absent	3071	135
( <i>Sebastolobus alascanus</i> )	Observed present	492	777
Adult Pacific ocean perch	Observed absent	2485	642
( <i>Sebastes alutus</i> )	Observed present	525	823
Rougeye and blackspotted rockfish	Observed absent	2709	895
( <i>Sebastes aleutianus</i> and <i>S. Melanostictus</i> )	Observed present	209	662
Shortraker rockfish	Observed absent	4063	124
( <i>Sebastes borealis</i> )	Observed present	66	222
Sharpchin rockfish	Observed absent	4039	174
( <i>Sebastes zacentrus</i> )	Observed present	158	104

The habitat model-based abundance index did not track the CPUE estimated from the stratified random sampling formulae particularly well in the cases of Pacific ocean perch and rougeye and blackspotted rockfish (Fig. 4). The two indices of abundance were well correlated for sharpchin rockfish, shortraker rockfish and shortspine thornyhead, for which the habitat index mirrored the stratified estimate (Fig. 4). In most cases, the habitat-based index appeared to be smoother than was predicted by the trawl survey biomass estimate. The correlations between the habitat indices and the biomass estimates from the bottom trawl survey ranged from  $-0.20$  to  $0.80$ . The most notable deviation occurred for adult Pacific ocean perch for which the model-based index was negatively correlated with the biomass estimate (although the relationship was insignificant). The precision of estimates was generally higher for the model-based indices of CPUE than for the stratified random sampling estimates, with the exception of the estimates for shortspine thornyhead. The precision of the model-based estimates was also consistent across the time series, as opposed to the variable estimates determined for Pacific ocean perch with the survey data, for example.

## Discussion

The lack of significant spatial patterns in the residuals implies that the spatial autocorrelation detected in other analyses of trawl survey data (Swartzman et al., 1992) could be the result of spatial autocorrelation in habitat distribution. For example, regions of medium slope

generally occur on the shelf break in a contiguous area. Because medium slope areas are the preferred habitat for adult Pacific ocean perch, the autocorrelation in their distribution may be a function of the autocorrelation in the slope variable. Additionally, the slope variable itself was derived from kriging the bathymetry data for the Gulf of Alaska. Thus, the autocorrelation of slope values may have accounted for any spatial autocorrelation in the LCPUE data.

An interesting result was that the time series of the habitat model index tended to be smoother for most species than the biomass estimates calculated directly from the trawl survey. This result implies that the interannual variation in the biomass estimate may be at least in part related to interannual variability in the habitats sampled, rather than to the effects of fishing mortality, natural mortality, or recruitment. Because of their long-lived nature and low natural mortality, it is unlikely that any of the rockfish populations examined could truly vary as much as the survey-based biomass estimate implies. For example, the Pacific ocean perch biomass estimated by the survey ranged from 820,000 t in 2001 to 457,000 t in 2003 to 766,000 t in 2005, a range that seems unlikely given the long life span and old age at maturity of this species. The habitat-based abundance index predicts a smooth increase in Pacific ocean perch abundance over this time period, an increase that is probably more consistent with the biology of the organism. In the Gulf of Alaska both Pacific ocean perch and the rougeye and the blackspotted rockfish complex are managed by using age-structured models. These models incorporate natural mortality estimates, recruitment functions, catch and age data



from the commercial fishery, as well as biomass and age data from the bottom trawl survey to estimate the total size of the populations. In the Pacific ocean perch and rougheye and blackspotted rockfish time series, the habitat model-based indices of abundance were correlated with the predicted survey biomass from the stock assessment model (Fig. 5). For Pacific ocean perch, the results were very good ( $r=0.95$ ), whereas for rougheye and blackspotted rockfish the correlation was weaker ( $r=0.67$ ). This finding corroborates that the habitat model indices are consistent with the entire data set incorporated into the stock assessment, even though the habitat model indices do not necessarily track the interannual changes in biomass for these two species that was calculated with the stratified random sampling formulae of the bottom trawl survey.

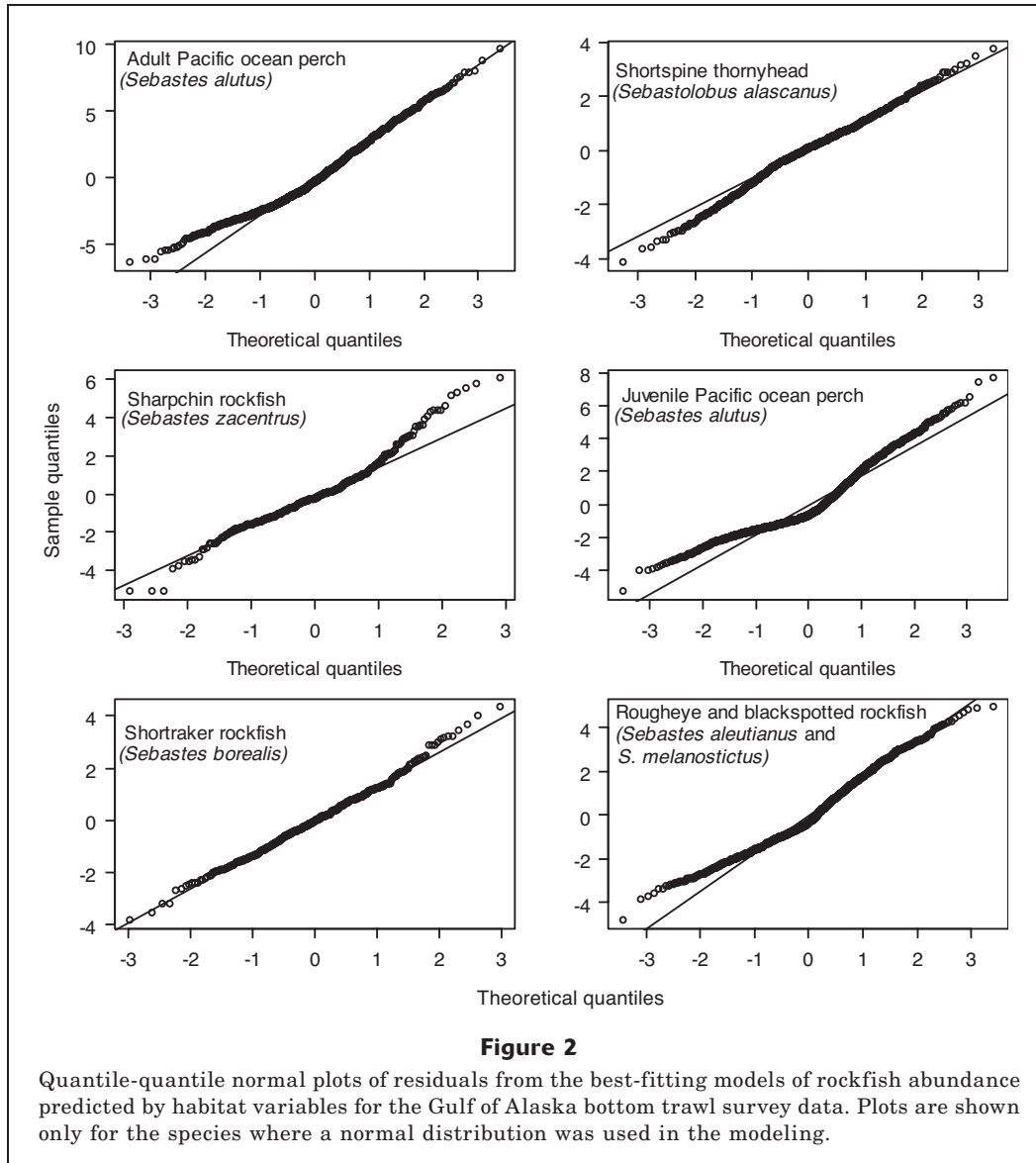
Although the model predicting rougheye and blackspotted rockfish LCPUE fitted reasonably well, there is no doubt that it could be improved by a clearer resolution of the two species. Because they are not easily identified in the field, even by biologists trained to distinguish them, it is not clear that the two species are found in the same habitats throughout their distributions. If the two species have distributions that are separated along environmental gradients such as depth, the inability to distinguish the two species would have negatively affected the model fits. This may have accounted for some of the variability not explained by the habitat model.

The variability around the points in the annual abundance indices was similar for the stratified bottom trawl survey estimate and the habitat models. However, the habitat model-based estimates of variability around the CPUE estimates were generally slightly smaller on average and consistent from year to year. The Pacific ocean perch CPUE time series from the stratified survey estimate showed inconsistent variability patterns, with narrow confidence bands in years of low abundance and wider confidence intervals in years of higher abundance. The habitat model-based estimates did not show this kind of variation and were much more consistent across years. The average CV for the

**Table 6**

Number of parameters in best-fitting habitat model (number of parameters in full model in parentheses), squared correlation coefficient between observed and predicted data ( $r^2$ ), and the relative contribution to predicting catch per unit of effort for significant variables included in each best-fitting model (zero indicates the variable was insignificant in the best-fitting model and – indicates this variable was not used in the modeling for that species). Relative contributions are not provided for dusky rockfish (*Sebastes variabilis*), harlequin rockfish (*S. variegatus*), and northern rockfish (*S. polyspinis*) because models explained <5% of the total variability in the log transformed catch-per-unit-of-effort data for these species.

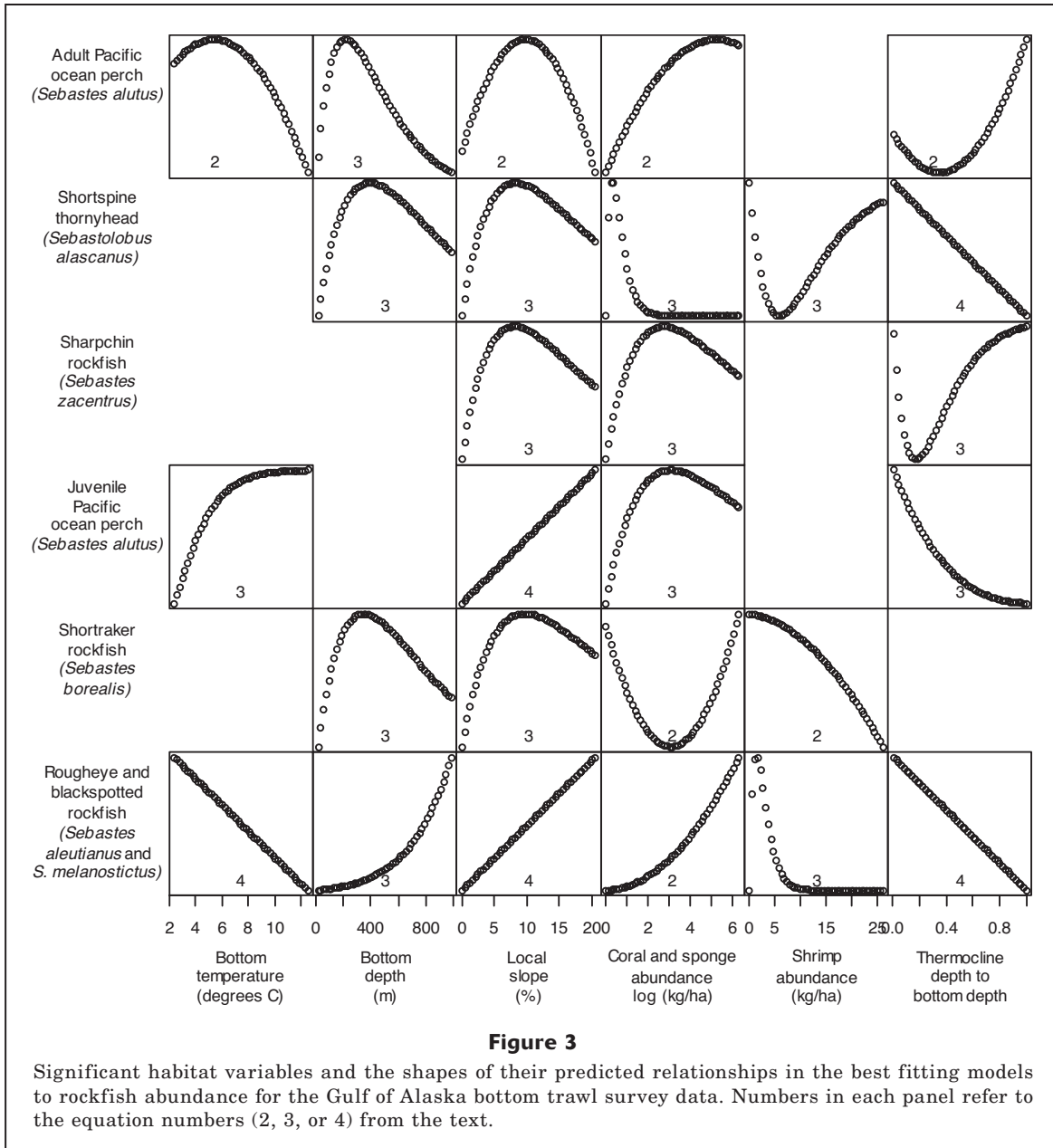
Species	Model parameters	$r^2$	Bottom temperature	Bottom depth	Local slope	Coral and sponge abundance	Thermocline depth/bottom depth	Shrimp abundance
Shortspine thornyhead ( <i>Sebastolobus alascanus</i> )	9 (18)	0.66	0	1.000	0.456	0.183	0.098	0.443
Shortraker rockfish ( <i>Sebastes borealis</i> )	10 (18)	0.60	0	0.310	0.748	0.666	0	1.000
Rougheye and blackspotted rockfish ( <i>Sebastes aleutianus</i> and <i>S. melanostictus</i> )	10 (18)	0.38	0.013	1.000	0.011	0.093	0.008	0.114
Sharpchin rockfish ( <i>Sebastes zacentrus</i> )	6 (15)	0.32	0	0	1.000	0.254	0.044	—
Adult Pacific ocean perch ( <i>Sebastes alutus</i> )	14 (15)	0.30	0.116	0.420	1.000	0.255	0.132	—
Juvenile Pacific ocean perch ( <i>Sebastes alutus</i> )	7 (15)	0.22	1.000	0	0.122	0.326	0.058	—
Dusky rockfish ( <i>Sebastes variabilis</i> )	7 (15)	0.03						
Harlequin rockfish ( <i>Sebastes variegates</i> )	13 (15)	0.03						
Northern rockfish ( <i>Sebastes polyspinis</i> )	12 (15)	0.01						



model-based estimate (0.21) was slightly smaller than the stratified estimate (0.24). Shortspine thornyhead was the only species for which there was a noticeable difference between the two methods in the variability around the point estimates of CPUE each year. The habitat model-based estimates had much larger confidence intervals than the stratified survey estimates. It could be argued that the estimates provided by the stratified survey were unreasonably small, because the average coefficient of variability was ~7% across years. It is unclear why the habitat model-based estimates had higher variability in this case.

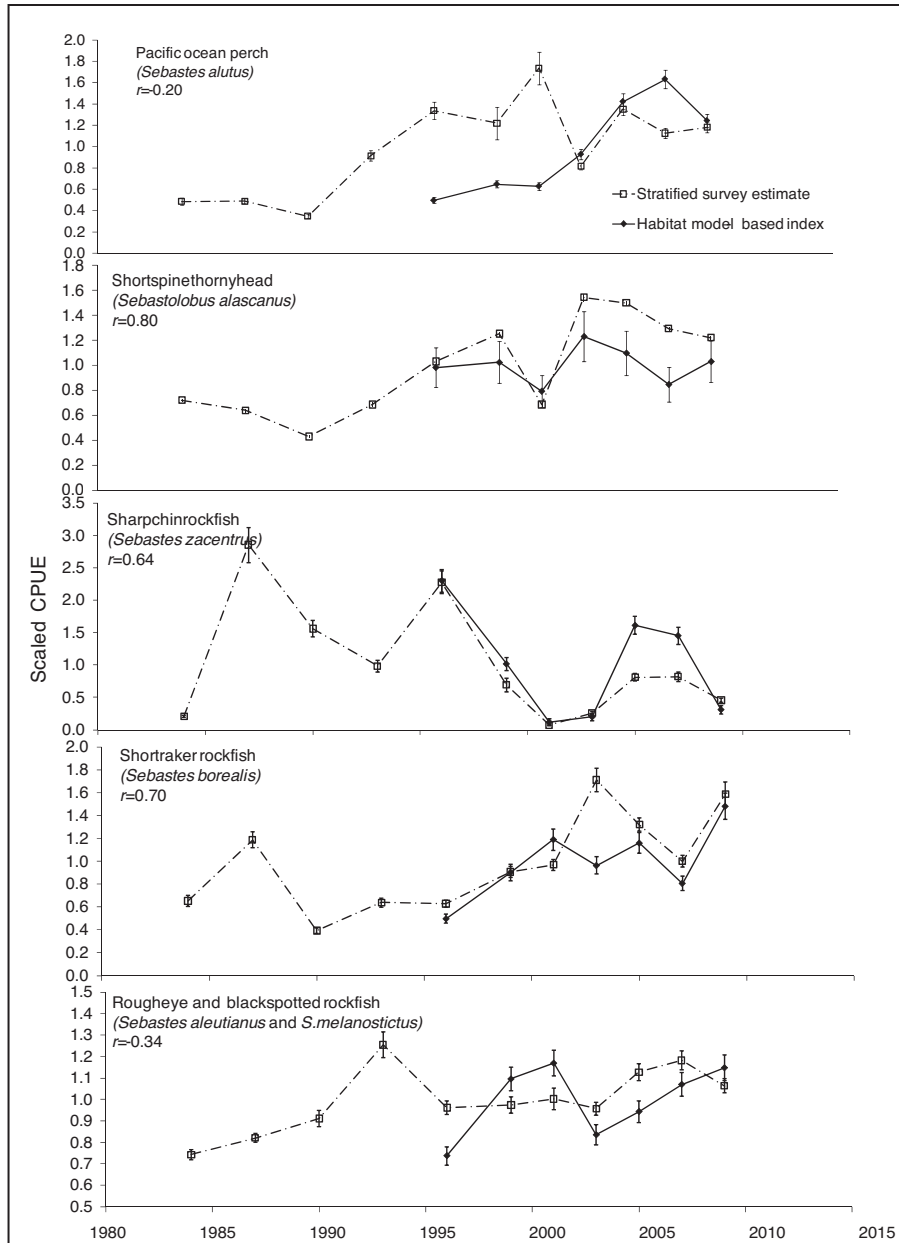
The habitat model-based abundance index presented here is different from other model-based indices in the methods used to model abundance. For one, it is rare to model a fisheries-independent data set. Modeling fishery-collected data to derive an abundance index

is much more common (Maunder and Punt, 2004). Previous model-based abundance indices have been produced for shortbelly rockfish (Field et al., 2007), as well as other fish species (Goodyear, 2003) with varying levels of success. These models have generally used a combination of generalized linear or additive modeling, with a two-stage model predicting presence and absence and then abundance (Maunder and Punt, 2004). This approach is similar to ours, but the model forms presented here were chosen *a priori* based on probable ecological relationships with resource continua (May, 1973). The resulting models may be more robust to changing patterns in the bottom trawl survey data because the habitat variables used in our analysis were chosen to reflect major processes influencing distribution, as well as the survival and growth for rockfish species.



Most of these variables were proxies for the actual habitat characteristics that could be measured, such as the thermocline depth-to-bottom-depth ratio as a proxy for water column production. Some of the other variables were not directly collected at the bottom trawl location, such as local slope (taken from depth contours). Direct measurement of the important variables would no doubt have improved the ability of the models to predict rockfish abundance and presence or absence. Additionally, there were probably some habitat processes that were missing from the analyses because there was a lot of unexplained variability in all of the models. Some of the habitat variables did not perform as expected. In particular, shrimp abundance was negatively correlated

to the abundance of two of the three shrimp-eating species. Thermocline depth-to-bottom-depth ratio was also negatively correlated with the abundance of three of the five species examined and insignificant for an additional species. These were disappointing results in that it was expected that the proxies for prey abundance would be positively correlated to abundance. There are two potential explanations for this disagreement. It is likely that, for example, the habitat preference for shrimp may not be the preferred habitat for shortraker and rougheye and blackspotted rockfish. It is also true that trawl survey stations where the water column was more evenly mixed occurred away from the continental shelf break (in more nearshore areas); whereas most of the species



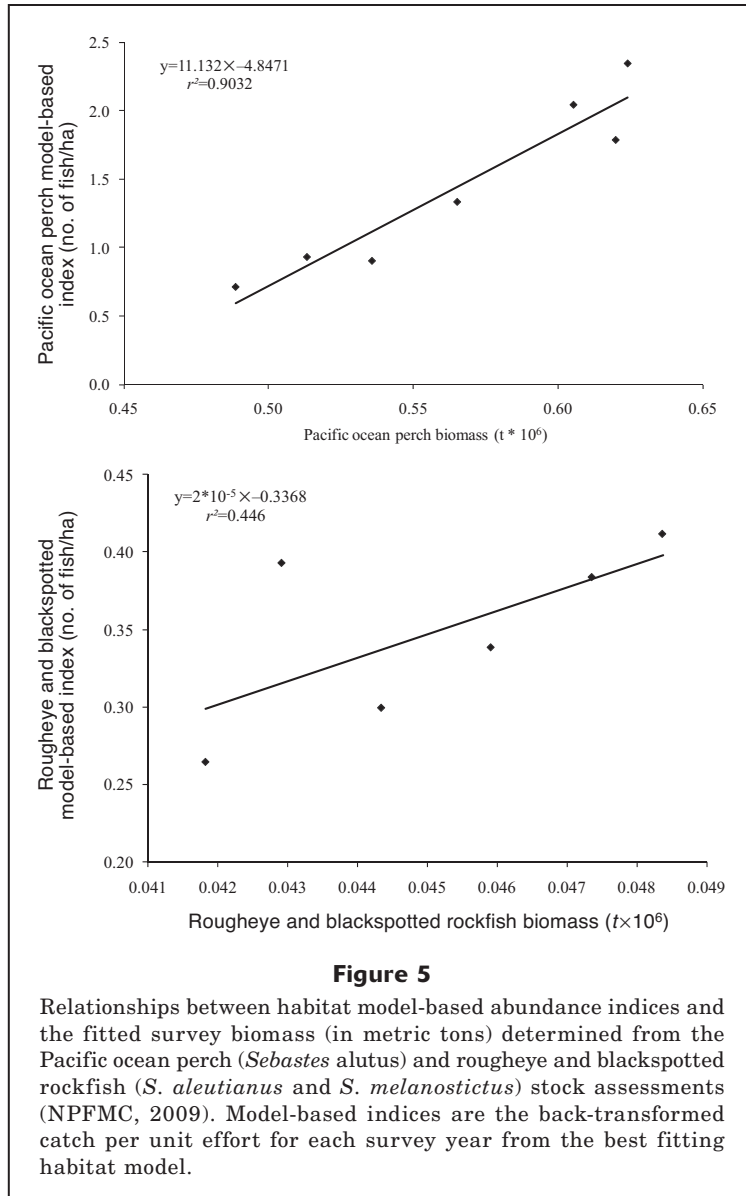
**Figure 4**

Scaled (to the average) catch per unit of effort (CPUE) time series from the Gulf of Alaska bottom trawl survey and rockfish habitat model-based indices. The 95% confidence intervals are shown for each data point or model prediction. Stratified survey CPUE estimates were calculated by using stratified random sampling methods (Wakabayashi et al., 1985). Model-based indices were the back-transformed to CPUE for each survey year from the best-fitting habitat model. Correlations between the two time-series for each species are also shown ( $r$ ).

of rockfish tended to prefer areas of higher slope and deeper depth near the continental slope. This mismatch between prey productivity and habitat preference for the rockfish species examined could explain part of the reason why the variables expected to represent variable food production did not behave as expected. It is also

likely that because these variables were proxies for processes that were not measured, they did not reflect feeding conditions at all.

The habitat-based indices of abundance presented here would benefit from better measurements of important variables. For example, even though water column



characteristics have been found to be related to rockfish growth and condition in other studies (e.g., Boldt and Rooper, 2009), a more direct measure of zooplankton abundance throughout the Gulf of Alaska would undoubtedly be more useful in explaining rockfish catches than the proxy variable related to the depth of the thermocline. A measure of substrate type would also be useful in this type of modeling study, but this information is unavailable for most of the Alaskan seafloor. Knowing substrate type at each of the survey stations would improve the predictive ability of the models, especially for those species whose presence or absence was not well determined (northern rockfish, dusky rockfish, and harlequin rockfish) because these are species that have a predilection for rocky, untrawlable habitats. Additional information on these two habitat variables (food availability and substrate type) are critical for

improving future distribution modeling for rockfishes throughout their ranges and improving our ability to identify trends in rockfish population abundance from bottom trawl survey data.

### Conclusions

In most age-structured models used for rockfish assessment in Alaska, the catchability parameter,  $q$ , can account for differences in the accessibility of a population to the bottom trawl survey gear. The fitted survey abundance trend in these stock assessments are usually a smooth time series of abundance, similar to what we observed in this modeling study. Thus, the habitat-based indices appear to result in the same smooth trends in the population as those determined with stock assess-

ment methods. The uncertainty about the trends in rockfish populations may be reduced by using habitat modeling to account for some of the variability in the survey data since the current stratified abundance indices produce biologically unrealistic variation in abundance estimates among years. Thus the habitat-based indices may provide for stock assessment models a more stable alternative to current biomass estimates produced by the multispecies bottom trawl survey in the Gulf of Alaska.

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