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ASSOCIATIONS BETWEEN THE ALASKA STELLER SEA LION DECLINE AND COMMERCIAL FISHERIES

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Abstract. The Steller sea lion (SSL) population in Alaska was listed as threatened under the Endangered Species Act in 1990. At that time, several procedural restrictions were placed on the commercial fisheries of the region in an effort to reduce the potential for human-induced mortality on sea lions. Several years have elapsed since these restrictions were put into place, and questions about their efficacy remain. In an effort to determine whether or not fisheries management measures have helped the SSL population to recover, estimates of the fishing activity of the Bering Sea/Gulf of Alaska commercial fisheries in the vicinity of individual SSL rookeries and SSL population trends at those rookeries were made using data from the National Marine Fisheries Service (NMFS) Fisheries Observer Program and Steller Sea Lion Adult Count Database. Fisheries data from 1976–2000 were analyzed in relation to SSL population counts from 1956–2001 at 32 rookeries from the endangered western stock. Linear regression on the principal components of the fisheries data show that a positive correlation exists between several metrics of historical fishing activity and the SSL population decline. The relationship is less consistent after 1991, supporting a hypothesis that management measures around some of the rookeries have been effective in moderating the localized effects of fishing activity on SSL.

Key words: commercial fishing; Eumetopias jubatus; *population decline; Steller sea lion.*

Introduction

This study investigates the statistical association between records of fishing activity and measures of population decline at rookeries in the western stock area of the Steller sea lion (*Eumetopias jubatus*). This population as a whole declined dramatically in the last 30 years. Index counts of Steller sea lions (SSL) made by the National Marine Fisheries Service (NMFS) in the late 1970s and 1996 show a decline from 109 880 to 22 223 animals breeding west of 144° W longitude (Bickham et al. 1996, Loughlin 1997). Due to this severe decline, the western stock of SSL was listed as "threatened" under the Endangered Species Act (ESA) in 1990, and was "uplisted" to "endangered" in 1997. Legal protections of SSL and their habitat began in mid 1990, under the ESA; these protections included area closures, and temporal and spatial redistribution of the fishing effort in the Bering Sea and Gulf of Alaska (Fritz et al. 1995).

Fishing was assumed to be a contributing factor in the SSL decline, because the expansion of the fishery roughly coincided with the period of the decline (Braham et al. 1980, Megrey and Wespestad 1990, Alverson 1991, Hanna 2000), and because some fisheries target some of the same species and size classes of fish that are utilized by SSL (Lowry 1982, 1986, Alverson 1991). Fisheries activities could plausibly affect SSL populations by changing fish species composition, distribution, and/or abundance in a way that decreases SSL foraging efficiency. Fishing can remove or disperse large aggregations of fish from an area (Baraff and Loughlin 2000), and can also result in reduced overall levels of fish biomass (NMFS 2000). Pinnipeds may abandon a traditional foraging region, or change their foraging patterns, as a result of such fisheries related disruptions (NMFS 2000). Furthermore, direct kill of SSL by fishers in defense of gear or catch, as well as SSL being caught in fishing gear incidentally, may have contributed substantially to SSL mortality in the 1970s (Loughlin and Nelson 1986, Merrick et al. 1987, Perez and Loughlin 1991).

Some cases of food shortages resulting in local depletions of otariid pinniped stocks have been documented. For example, the northern fur seal (*Callorhinus ursinus*) population on the San Miguel Islands dropped considerably during the El Nino Southern Oscillation (ENSO) events of the early 1980s (DeLong and Antonelis 1991). Aureioles and Le Boeuf (1991) noted lowered California sea lion (*Zalophus californianus*) pup production in parts of Mexico, also resulting from ENSO events in 1982 and 1983.

Documented cases of fisheries activities negatively affecting pinniped populations are rare. However, the Barents Sea harp seal (*Pagophilus groenlandicus*) population suffered increased juvenile mortality due to food shortages resulting from the fisheries-induced collapse of

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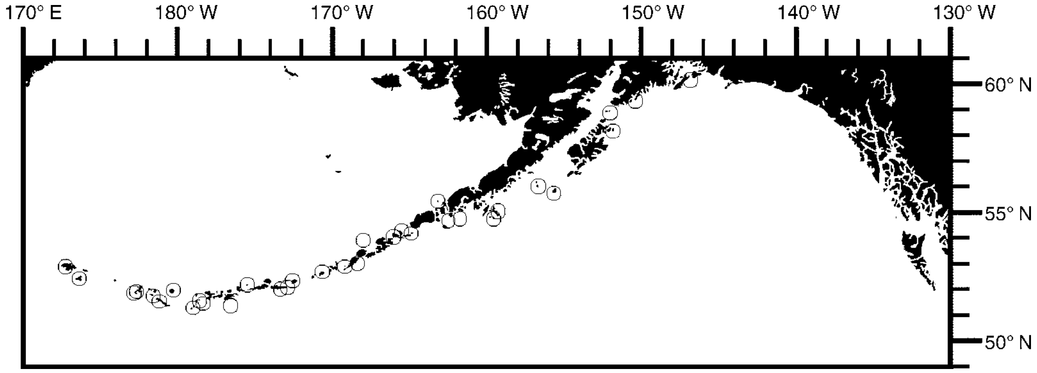

FIG. 1. Map of the Steller sea lion rookeries used in this analysis.

the capelin (*Millotus villosus*) stock in the 1980s (Baraff and Loughlin 2000).

Several previous studies have attempted to find connections between SSL population trends and fishing activities (Loughlin and Merrick 1988, Ferrero and Fritz 1994, Sampson 1995). All three previous studies concentrated only on particular species of fish. Loughlin and Merrick (1988) and Ferrero and Fritz (1994) looked at only walleye pollock (*Theragra chalcogramma*), while Sampson looked at pollock, Pacific cod (*Gadus macrocephalus*), and Atka mackerel (*Pleurogrammus monopterygius*). The present analysis examined entire hauls, including bycatch, in addition to particular species of fish. The three previous studies used only photographic SSL count data from the late 1970s, up to some point previous to the publication of their results. The present study extends the SSL time series in both directions, using photographic data from the 1950s as well as ocular estimates from the 1960s and early 1970s, in addition to recent photographic counts, which run through 2001. The present study also examined fishing data found at a range of distances from SSL rookeries, where the previous studies tended to focus on fixed geographic areas or a single distance from SSL rookeries. Sampson (1995) compared fishing in different seasons to SSL trends; the present analysis examines seasons, as well as different types of fishing gear. Finally, the present study considers cumulative fishing over a number of years, while the previous studies used catch in individual years as their measure of fishing.

Although none of these previous studies found conclusive evidence of a relationship between fisheries activities and the SSL decline, this study was initiated under the hypothesis that fisheries have had a negative effect on SSL and that conservation measures have helped to mitigate that effect.

METHODS

SSL count data

The Steller sea lion data used here come from the National Marine Fisheries Service Adult Count Database. Adult SSL are usually counted using photographs taken from low-flying aircraft. Some of the data, especially those data recorded during the 1960s and early 1970s are from ship- or land-based estimates, using ocular methods (binoculars or spotting scopes). Ocular counts were generally regarded as less reliable than overhead, photographic counts (Merrick 1987). The analysis reported here incorporates all the available data recorded during the peak of the breeding season, that is, the months of June and July (Calkins and Pitcher 1982), for major SSL rookeries, west of 144° W longitude (i.e., the western stock, or endangered population of SSL, Fig. 1).

Fitting the SSL decline rate

The natural log of the observations (number of adults present on land, at the time of observation) for each rookery, were fit using regression to a two-stage linear regression model, implying two periods of geometric growth, at possibly different rates. The two-stage model fits three parameters. The first is a slope estimate, starting at the year corresponding to the first observation recorded at that site and ending at 1991. For example, if the first observation at the Marmot Island rookery was recorded in 1957, the first slope parameter will be the slope of the line that "best" fits the natural log of the observations from 1957 to 1991 subject to the constraint that this line also connects 1991 with the "best"-fit line after 1991. The second parameter is a 1991 intercept. The model uses 1991 as a hinge point because active restrictions on the Bering Sea and Gulf of Alaska fisheries, around SSL rookeries began then (NMFS 2000). The last parameter of the two-stage regression model is the slope estimate for the years 1991–2001.

The earliest SSL data are not often used in analyses because there have been questions about their accuracy (e.g., Withrow 1982). To explore the effects of possible accuracy problems with the early counts, several different starting points for the two-stage regression model are employed here. The first two-stage regression estimates were made using all the available data from 1956 on. These estimates are referred to as year-of-first-census (YFC) (50s) 1991 slope, 1991 intercept (50s), and 1991–2001 (50s) slope. The counts from the 1950s were generally lower than counts from the 1960s, and counts later than the 1960s reflect the range-wide decline of SSL (Trites and Larkin 1992). This results in trajectories from some rookeries having a peak shape, with its apex somewhere in the 1960s. This pattern is not fit well with a single straight line, but the data are too sparse to identify the date of the reversal. Since a only a few of the SSL rookeries were sampled in the 1950s, only some of the sites show a poor fit using YFC 1991 as the first slope estimate. However, in order to examine the influence of the sites that were poorly fit, a second set of SSL population parameter estimates were made, without the data from the 1950s. These estimates will be referred to as YFC (no 50s) 1991 slope, 1991 intercept (no 50s), and 1991–2001 (no 50s) slope. Furthermore, I also examined the SSL data subset confined to the years for which fisheries observer data were available. That is, SSL population parameter estimates were also made using the data from the years 1977–2001. These estimates will be referred to as 1977–1991 slope, 1991 intercept, and 1991–2001 slope.

This SSL population trajectory model was fit numerically using Marquardt's Algorithm, which in this case was used to find the parameter values that minimized the squared residuals from the regression fit in the log space. There were 32 rookeries with enough data to reasonably estimate all three parameters. Attu Cape Wrangell (52°55′02″ N, 172°27′54″ E) had enough observations that occurred after 1991 to estimate the 1991–2001 slope and was used in analyses of that period, while Agattu (52°22′14″ N, 173°42′36″ E) had enough pre-1991 observations to be used in the YFC 1991 analyses, resulting in a sample size of 33 rookeries for each analysis. Two composites were created from counts of component rookeries in the Adak Complex (51°21′9″ N, 176°35′04″ W) and Ugamak Complex (54°13′14″ N, 164°47′52″ W), respectively, in order to make use of data that were recorded under different site-naming protocols before and after 1991. These respective composite rookeries are aggregates of closely spaced rookeries. Otherwise, the unit of SSL population used in this analysis was the individual rookery. In order to avoid double counting of fisheries data around them, composite sites were assigned a single nominal latitude and longitude, located at the centroid of the included sites (Fig. 1).

Measures of fishing activity

The SSL data were compared to fisheries data from the NMFS Fisheries Observer program. The Observer program began in 1977, and placed trained NMFS observers on fishing vessels who monitored various characteristics of the catch. Among the many data recorded by observers were the global position (latitude and longitude) and weight of each individual haul made while the observer was "on effort," or working. Not all fishing vessels had observers during any one season. To correct for the fact that only a fraction of the total fishing was "observed," observer coverage rates were extracted from NMFS summaries of observer activity and from individuals involved in the observer program (Nelson et al. 1978, 1979, 1980, 1981, 1982, 1983, Wall et al. 1978, 1979, 1980, 1981, 1982, Berger et al. 1984, 1985, 1988, Berger and Weikart 1988, 1989, Guttormsen et al. 1990, 1992; J. Berger, *personal communication*; L. Fritz, *personal communication*). These sources report the percentage of the total fishing days that were "observed" during each calendar year, in both the Being Sea and Gulf of Alaska. The quantities derived from each haul during a given year were then expanded by a factor equal to the inverse of the proportion of hauls observed for that year, in that area (Bering Sea vs. Gulf of Alaska).

The fishing variables used in this analysis are the estimated total number of fishing events (hauls), the sum of the weights of all hauls, the duration of time that the gear was at fishing depth, and the catch per unit effort (CPU; the summed weight of all hauls divided by the summed duration of time that the gear was at fishing depth) that occurred within varying distances from each SSL rookery in a time period. In some years, the duration that the gear was at fishing depth was not recorded for every observation (particularly in 1984). In these cases, duration values were bootstrapped, using a uniform distribution with replacement, from existing duration values that matched the missing data in time period, season, gear type, and target species. The variables, number of hauls, sum of the weight of hauls, and duration of fishing can be thought of as measures of fishing activity. CPU can be thought of as a rough measure of fish abundance, before fishing took place, if other aspects of the gear were comparable. Fishing that occurred within distances of 10, 20, 30, 50, 100, 10–20, 10–30, and 20–30 km, from each SSL rookery were analyzed.

Because the type of fishing gear used affects the size and composition of the haul, the fishing data were also stratified by gear type. The fishery data were divided into 10 different gear types, five of which, mothership/processor vessel, small trawl/nonpelagic trawl, large trawl/pelagic trawl, pot or trap, and longline, were used near SSL rookeries. "Mothership" was not strictly a gear category, but represented a type of fishery in which several smaller "catcher vessels" brought their catch directly to the mothership for at-sea processing. During the "joint venture" (JV) fishery period (a period when much of the fishery was prosecuted by domestic catcher boats providing fish to foreign processor ships), observers were not generally stationed on the domestic catcher vessels, so the only data on specific hauls for that period came from motherships, which often carried observers (Berger and Weikart 1988). These observers, however, recorded information on each delivery made by a catcher boat. Therefore the sum of the weight of the haul and duration of fishing events using "mothership gear" were the values reported by catcher vessels and the number of hauls referred to the number of deliveries made, instead of the number of individual hauls made by catcher vessels. Data from the foreign fisheries did not distinguish between pelagic and nonpelagic trawl gear, but rather divided trawl boats by their size. The combination of small boats with nonpelagic trawls and large boats with pelagic trawls, therefore, was not a finely discriminating characterization of the gear. There was, however, very little overlap between the foreign and domestic fisheries in the time periods used in this analysis. Data collected on domestic vessels were scarce until 1990, so there was only one year of noteworthy overlap between the designations "small" with "nonpelagic" and "large" with "pelagic." The timing of fisheries removals may have been important, so the fishing data were also stratified by season. December, January, and February collectively were referred to as winter; March, April, and May were spring; June, July, and August were summer and September, October, and November were fall. Because there are many possibilities for stratification in this data set, many analyses of the same sets of variables were necessary.

The values recorded for the fishing variables were not normally distributed. There were many near-zero values and a few very large values. The ranks of fishing variable values were substituted for the raw variable values in order to obtain a more even distribution of values and reduce the influence of possible nonlinearity in relationships. In this transformation, the lowest value for a fishing variable would receive the value 1, and the next higher value would receive the value 2, and so on.

Management or conservation measures and expected outcomes

The Bering Sea and Gulf of Alaska fisheries have been subject to many regulations changes, several of which were first instituted around 1991, in response to the listing of SSL under the Endangered Species Act. In mid-1990, shooting at or near SSL was banned and the number of SSL that could legally be killed, incidental to fishing operations, was lowered. A 3 nautical mile (5.6 km) "no entry" buffer zone was immediately established around major SSL rookeries and, by January 1992, a 10 nautical mile (approximately 18 km) trawl exclusion zone was in place around 37 rookeries in Alaska. In 1991, alterations were made to the fisheries management plan for pollock, with the intention of spreading out the fishing effort for these species over time and space (NMFS 2000). In 1993, the Atka mackerel fishery management plan was altered as well, though changes to the Atka mackerel management plan were not instituted in response to SSL protections under the ESA. They were however, consistent with the conservation objectives for Steller sea lions (NMFS 2000).

If effective, these measures could reasonably be expected to reduce any direct mortality of SSL caused by fisheries. One would further expect any negative interaction between fisheries and SSL to move off-shore, away from SSL rookeries. Alterations to fishery management plans should also have reduced the strength of association between the SSL decline and trawl operations, as well as the pollock and Atka mackerel fisheries in particular.

Analysis of the association between fishing and the SSL decline

Fishing that occurred from 1977 to 1991 was compared to the SSL slope estimates for the years YFC 1991, where YFC is the year of first (accepted) census at that site.

Fishing that occurred from 1991 to 2000 was compared to the slope estimates for the years 1991–2001 at each site. Note that the 1991–2001 slope estimates differed, depending on which starting point for the earlier period was used, because of the effect of the early period data on the 1991 intercept estimate.

SSL decline estimates, by rookery, were related to individual fishing variables as measured near the corresponding rookery using simple linear regression (SLR) where fishing was the independent variable and SSL population trajectory was the dependent variable. Thus, the sample size in each regression was the number of rookeries. Some fishing variables tended to be very large in value, while the slope estimates based on the natural log of SSL population were near zero. Therefore, all variables were standardized to have a mean of zero and a standard deviation of one. The P values in this stage of the analysis tested whether the regression coefficient corresponding to each predictor variable was different from zero.

The relationship between the SSL decline rate and groups of fishing variables was examined by using the principal components of available fishing variables that occurred before or during each segment of the SSL population decline, as predictors of each respective SSL population slope estimate, in a series of multiple linear regressions (MLR). Each principal component that accounted for more than 2% of the total variation in the data was included in competing MLR models. All possible combinations of these principal components were tested and the model that produced the highest R^2 value (adjusted for the number of variables used in the MLR) was selected.

RESULTS

Associations before 1991

The results of many of the SLR comparisons of SSL population trend and commercial fishing variables are shown cumulatively (Figs. 2–5). The results of many different SLR are plotted in the same figure. Each SLR corresponds to a different fishing variable. The results for number of hauls in a time period (num), sum of the weight of all hauls over a time period (sum), and the duration of time gear was at fishing depth (dur) tended

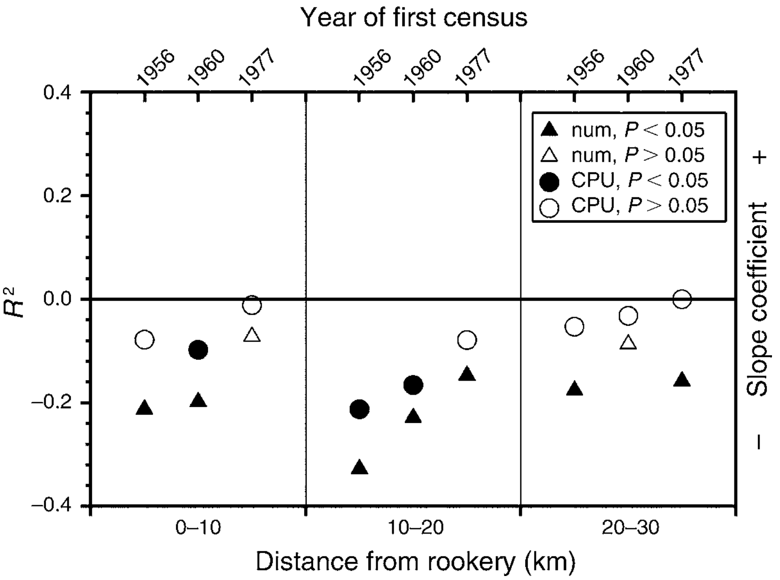

FIG. 2. Results from linear regressions using fishing variables to predict year-of-first-census to 1991 Steller sea lion (SSL) population trend. Variables are CPU (catch per unit effort, the summed weight of all hauls divided by the summed duration of time that the gear was at fishing depth) and num (the number of hauls in a time period).

to produce similar results, so only num was plotted in figures. The x-axis indicates the different distances from SSL rookeries tested. If a SLR resulted in a negative slope coefficient, meaning that higher fishing variable values predict a lower SSL population growth trend, then the point corresponding to that particular SLR is plotted below the $y = 0$ line (in negative y space). If a positive slope coefficient was found, the point corresponding to that particular SLR is plotted above the $y = 0$ line (positive y space). The absolute value of displacement from the origin on the y axis is equal to the R^2 value found in each SLR.

The general negative relationship between fishing and SSL population trend (Fig. 2) prompted an in-depth investigation of which particular seasons, species, and gear might be driving the pattern. Data from this analysis indicated a consistent and relatively strong relationship between summer and fall small/nonpelagic

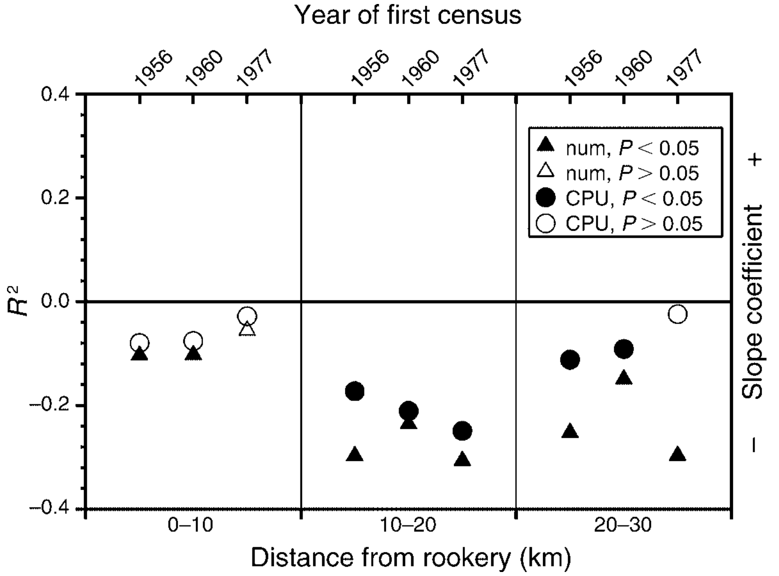

FIG. 3. Results from linear regressions on summer fishing using small-trawl vessels to predict year-of-first-census to 1991 SSL population trend. Variables are as defined in Fig. 2.

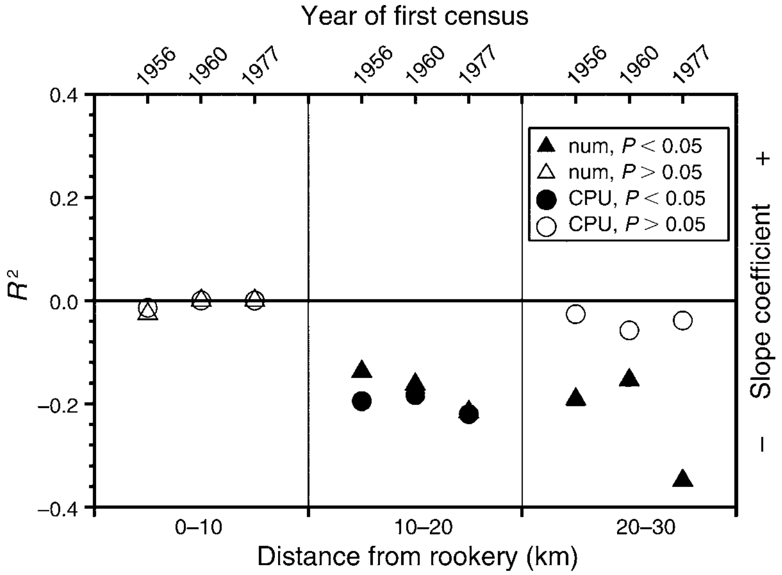

FIG. 4. Results from linear regressions on fall fishing using small-trawl vessels to predict year-of-first-census to 1991 SSL population trend. Variables are as defined in Fig. 2.

trawl fishing for all species and SSL population trend (Figs. 3 and 4). This relationship is uniformly negative, meaning that high ranks in fishing measures were associated with the most severe SSL population declines.

Principal components analysis and multiple linear regression

PCA of pollock, Pacific cod, and Atka mackerel, small/nonpelagic trawl fishing, during the summer and fall at 10–20 km from SSL rookeries between the years 1977 and 1991, supports the conclusion that high ranks in fishing measures were associated with the steepest SSL declines. The first principal component was made up of positive correlations between all the variables and explains 71.0% of the variation in the data (Table 1). A high rank in one measure of fishing was positively correlated with a high rank in any other fishing measure (Fig. 6). The MLR results (Table 2) show that in each

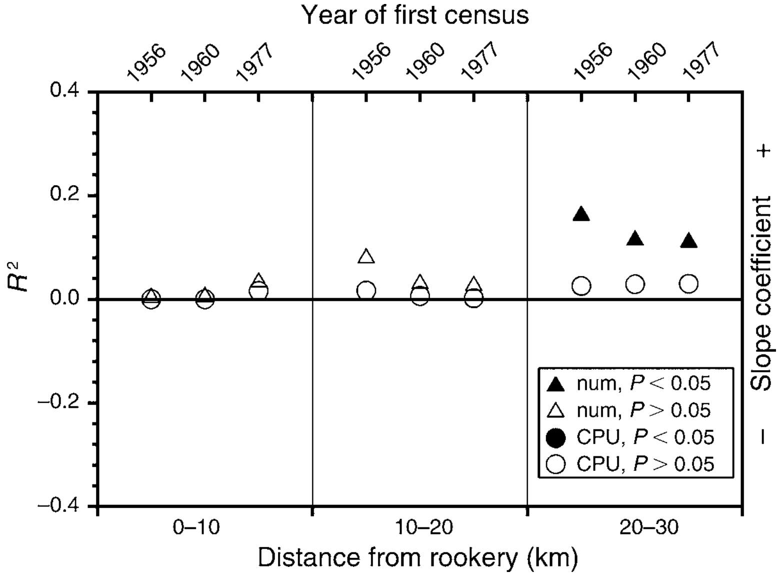

FIG. 5. Results from linear regressions using all gear, in all seasons, to predict SSL population trend after 1991. Variables are as defined in Fig. 2.

TABLE 1. Eigenvalues associated with the first eight principal components from a PCA of pollock, Pacific cod, and Atka mackerel small-trawl fishing, during the summer and fall at 10–20 km from SSL rookeries between the years 1977 and 1991.

Eigenvalue	Total variation (%)
16.53	71.00
1.882	8.10
1.612	6.90
1.009	4.30
0.651	2.80
0.425	1.80
0.375	1.60
0.228	1.00

case, regardless of the YFC, scores from PC1 were a significant and negative predictor of SSL population trend before 1991. Sites that score highly on PC1 tended to have high ranks in most fishing variables. Therefore, the negative slope coefficient corresponding to PC1 indicates that sites with high fishing variable ranks were associated with steep SSL declines.

Scores from PC4 were included in the MLR using YFC (50s) 1991 and YFC (no 50s) 1991 SSL population trend estimates as response variables. PC4 was not a significant predictor in either case. PC3 was included in the MLR using the 1977–1991 SSL population trend estimate as the response variable. PC3 score was a significant predictor. PC3 described variation due to differences between rank in pollock and Pacific cod fishing and Atka mackerel fishing (Fig. 6). Sites with high PC3 scores generally had relatively high Atka mackerel ranks and relatively low pollock and Pacific cod ranks. The slope coefficient associated with PC3 was positive, indicating that high Atka mackerel fishing variable ranks and relatively low pollock and Pacific cod ranks were associated with less severe SSL declines. PC3 was significant only in the MLR that uses 1977–1991 SSL slope as the response variable. Differences between Atka mackerel fishing and fishing for other species may be worth investigating further, but this analysis focused on results that were consistent across all three SSL population trend estimates.

PC1 demonstrates that most of the variation in the 1977–1991 fishing data can be explained by the extent to which the various measures of fishing were correlated to each other. PC1 score, in combination with one other component score, can explain about 30% of the between-rookery variation in SSL population trend before 1991 (Table 2).

Associations after 1991

The nature of the relationship between fishing and the SSL decline was dramatically different when the SSL population trend estimates after 1991 were used as the response variable. The significant relationships result from comparisons of offshore (>20 km) fishing. Furthermore, the significant slope coefficients in these regressions were uniformly positive, indicating that high ranks in fishing measures were associated with less severe SSL declines over this time period (Fig. 5).

Principal components analysis and multiple linear regression

MLR using principal component scores derived from PCA analysis of fishing variables from 1991–2000 reinforce the findings described above. When 1991–2000 fishing was used to predict 1991–2001 SSL population trend, the slope coefficients corresponding to principal components 1 and 3 were significant and positive, while the slope coefficient corresponding to PC5 was significant and negative, in each of the MLR

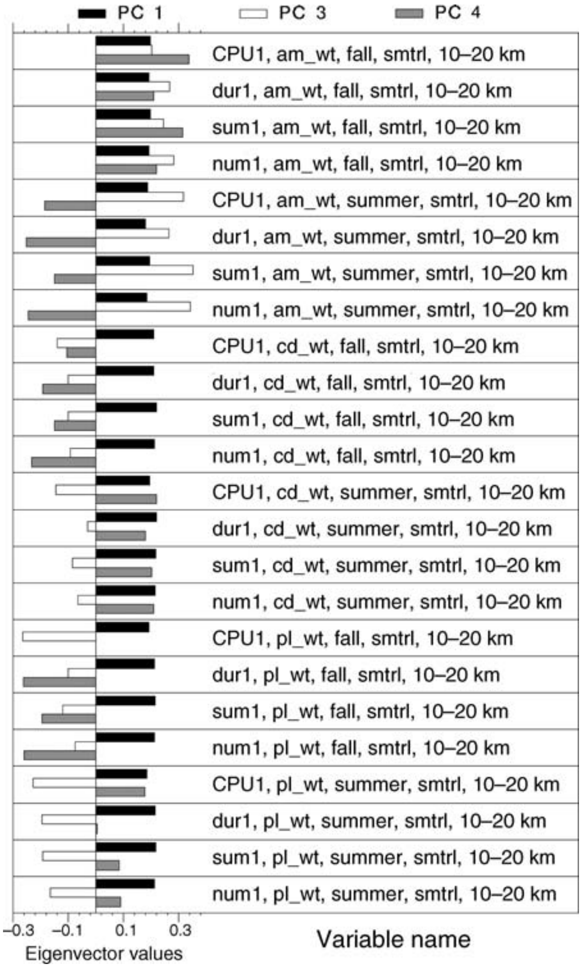

FIG. 6. Eigenvector values corresponding to principal components 1, 3, and 4 from a PCA of 1977–1991 fishing variables. Variables are CPU (catch per unit effort, the summed weight of all hauls divided by the summed duration of time that the gear was at fishing depth); dur (duration of time gear was at fishing depth); sum (sum of the weight of all hauls over a time period); num (number of hauls in a time period); am_wt (Atka mackeral weight); cd_wt (cod weight); pl_wt (pollock weight); summer (June, July, and August); fall (September, October, and November); lgtrl (large-trawl vessel); smtrl (small-trawel vessel); 10–20 km (fishing conducted 10–20 km from shore).

Table 2. Results of MLR models using principal component scores as predictors of each year-of-first-census (YFC) 1991 Steller sea lion (SSL) population trend estimate.

Variable	Slope coefficient (β)	P	Adjusted R^2
YFC (50s) to 1991 SSL decline			
PC1	−0.535	0.001	0.3232
PC4	−0.273	0.071	
YFC (no 50s) to 1991 SSL decline			
PC1	−0.533	0.001	0.2669
PC4	−0.16	0.298	
1977–1991 SSL decline			
PC1	−0.466	0.003	0.3432
PC3	0.404	0.009	

Note: See *Methods: Fitting the SSL decline rate* for an explanation of the estimates.

models with the highest adjusted R^2 values (Table 3). PC1 was a component describing the positive correlations between all of the fishing variables (Fig. 7) and explained 53.4% of the total variation in the fishing data (Table 4). Sites with a high PC1 score tended to have high ranks in most of the fisheries variables, while sites with a low PC1 score generally had low ranks in most of the fisheries variables. Therefore, a positive relationship between PC1 score and 1991–2001 SSL population trend represented a positive relationship between fisheries variables and SSL population trend over that period.

PC3 explains 18.0% of the variation in the data set. PC3 reflected variation that is largely due to positive correlations between the CPU of large/pelagic trawl fishing for pollock in winter and the CPU of large/pelagic trawl fishing for pollock in spring, both at 0–100 km from SSL rookeries (Fig. 7). Sites with high PC3 scores tended to have high ranks in both those variables, while sites with low (negative) scores had low ranks in both variables. Sites with near zero PC3 scores tended to have large differences between the CPU of large/pelagic trawl fishing for pollock in winter and the CPU of large/pelagic trawl fishing for pollock in spring. The slope coefficient for PC3 was positive, indicating that areas of high offshore pollock abundance in winter and spring were associated with less severe SSL declines.

The slope coefficient for PC5 score was significant and negative. PC5 reflected variation in the data that was due to a negative correlation between CPU of large/pelagic trawl fishing for pollock in spring, and the num, sum, and dur variables for small/nonpelagic trawl fishing for Pacific cod in spring, all at 0–100 km from SSL rookeries on one side, and the CPU of small/nonpelagic trawl fishing for Pacific cod in spring at 0–100 km, together with the sum and CPU variables for small/nonpelagic trawl fishing for Pacific cod at 0–50 km on the other side (Fig. 7). High scores in PC5 resulted from high ranks in the CPU of large/pelagic trawl fishing for pollock in spring, and the num, sum, and dur variables for small/nonpelagic trawl fishing for Pacific cod in spring all at 0–100 km, coupled with low ranks in the CPU of small/nonpelagic trawl fishing for Pacific cod in spring at 0–100 km, and the sum and CPU variables for small/nonpelagic trawl fishing for Pacific cod at 0–50 km. Low PC5 scores would result from the opposite configuration. The slope coefficient associated with PC5 was negative, indicating that sites with high ranks in offshore pollock abundance in spring and high ranks in offshore, small/nonpelagic trawl Pacific cod fishing activity, coupled with low ranks in offshore, spring, Pacific cod abundance and offshore winter Pacific cod abundance as well as low ranks in total small/nonpelagic trawl catch, were associated with steeper SSL declines. PC5 explains only 3.5% of the total variation in the fishing data, indicating that the pattern is not particularly strong within the fisheries records.

In summary, the changes in the relationship between fisheries and SSL, from before 1991 to after 1991, were extensive and could be seen across most of the different fishing variables examined (Table 5).

DISCUSSION

The negative relationship between fishing activity variables and SSL population could be explained in a number of ways. One possibility is that repeated fishing in an area depleted the most easily accessible prey base over time, making it more difficult for SSL to satisfy their caloric requirements (Loughlin and Merrick 1988). Trites and Donnelly (2003) have recently concluded that SSL were probably nutritionally stressed during the decline.

If nutritional stress was indeed a major driver of the SSL decline, why are the fish abundance variables also negatively correlated with SSL population growth? CPU

Table 3. Results of MLR models using principal component scores as predictors of each 1991–2001 SSL population trend estimate.

Variable	Slope coefficient (β)	P	Adjusted R^2
1991 (50s) to 2001 SSL decline			
PC1	0.482	0.001	0.4326
PC2	0.2	0.145	
PC3	0.325	0.022	
PC5	−0.322	0.023	
PC6	0.153	0.261	
1991 (no 50s) to 2001 SSL decline			
PC1	0.454	0.003	0.3755
PC2	0.187	0.192	
PC3	0.291	0.047	
PC5	−0.324	0.029	
PC6	0.171	0.232	
1991–2001 SSL decline			
PC1	0.454	0.003	0.3793
PC2	0.19	0.183	
PC3	0.292	0.046	
PC5	−0.326	0.027	
PC6	0.169	0.236	

Note: See *Methods: Fitting the SSL decline rate* for an explanation of the estimates.

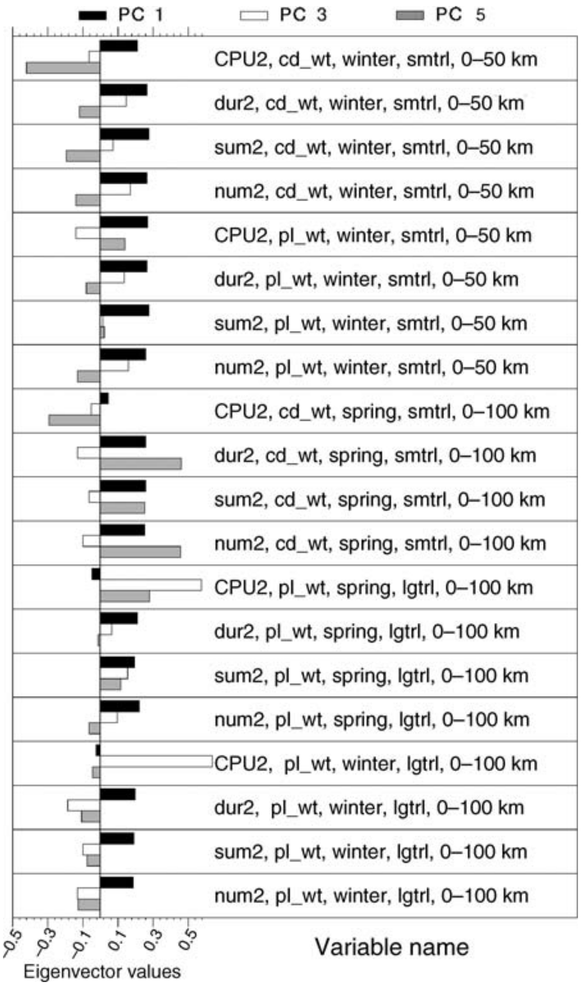

FIG. 7. Eigenvector values corresponding to principal components 1, 3, and 5 from a PCA of 1991–2001 fishing variables. Variables are as described in Fig. 6; and winter (December, January, and February); spring (March, April, and May); 0–50 km (fishing conducted 0–50 km from shore); 0–100 km (fishing conducted 0–100 km from shore).

reflects the abundance of fish present before the fishing took place. The fish abundance after fishing is unknown. It could be that fishing in a rich prey field caused localized depletions of frequently utilized SSL foraging patches, which might force SSL to have longer search times and thus greater energy expenditures.

Another possibility is that SSL were being caught and killed along with the fish (Loughlin and Nelson 1986), or simply shot from fishing boats during this period (Loughlin and Nelson 1986, Trites and Larkin 1992). In this case, all of the fishing metrics measured here would merely be reflecting the number of SSL being killed as a result of fishing related activities. That is, higher fishing activity and higher fish abundance were merely proxies for the frequent presence of fishermen, which might indicate high direct SSL mortality.

The strongest relationships generally occur at 10–20 km from rookeries. It should be noted that the fisheries data analyzed here probably do a poor job of describing fishing from 0–10 km offshore. Vessels smaller than 60 feet (18.46 m) in length are not required to carry NMFS observers (L. Fritz, *personal communication*). It is reasonable to conclude that these vessels do some of their fishing in relatively near-shore waters, due to range limitations and the need to be close to sheltering bays and breakwaters in case of severe weather. While the overall removal of fish by these vessels is probably small, (except in the case of sablefish; L. Fritz, *personal communication*) their contribution near-shore may be relatively important. Furthermore, the waters out to 3 nautical miles (5.6 km) from shore are state waters, managed by the Alaska Department of Fish and Game (ADF&G) and ADF&G data were not included in this analysis. Therefore, the absence of a pattern near shore may be due to lack of data, rather than lack of differences between rookeries.

The seasonality of the negative relationship between fishing and SSL population trend is also important. June and July are SSL breeding months, during which females begin nursing, and pups are entirely dependent on their milk (Sandegren 1970). Heavy fishing around SSL rookeries during the summer may lead to localized depletions of fish, reducing the near-rookery availability of SSL prey. Females do not leave the rookery for extended periods of time during the early stages of pup development (Sandegren 1970, Higgens et al. 1988, Maniscalco et al., *in press*). Therefore, any foraging they do is likely to be near shore in summer. Females may also require extra forage to produce sufficient milk for their new pup (see Plate 1). If the increased caloric requirements of nursing females are not met, young SSL may show reduced growth rates. This phenomenon has been seen in other pinniped species (Trillmach and Limberger 1985, Trillmach and Dellinger 1991). Trites and Donnelly (2003) review evidence indicating that juvenile growth rates of SSL were probably reduced during the 1980s.

There was also a consistent and relatively strong relationship between fall small/nonpelagic trawl fishing

TABLE 4. Eigenvalues from the PCA of ranked, winter and spring, large-trawl fishing for pollock and spring small-trawl fishing for Pacific cod at 0–100 km from SSL rookeries, and winter small/nonpelagic trawl fishing for pollock and Pacific cod at 0–50 km from SSL rookeries, from 1991 to 2000.

Eigenvalue	Total variation (%)
10.361	53.40
3.495	18.00
1.727	8.90
1.613	8.30
0.684	3.50
0.56	2.90
0.363	1.90
0.23	1.20

TABLE 5. Summary of correlations between various fishing measures and SSL population trends before and after 1991.

Measure	Correlation	
	Before 1991	After 1991
Nearshore fishing activity	–	none
Offshore fishing activity	none	+
Summer fishing activity	–	none
Fall fishing activity	–	none
Summer fish abundance	–	none
Fall fish abundance	–	none
Winter fishing activity	none	+
Spring fishing activity	none	+
Winter fish abundance	none	+
Spring fish abundance	none	+
Small-trawl fishing activity	–	+
Small-trawl fishing CPU†	–	+
Large-trawl fishing activity	none	+
Large-trawl fishing CPU†	none	+

Note: Positive correlation is denoted by +, and negative correlation is denoted by –.

† Catch per unit effort; the summed weight of all hauls divided by the summed duration of time that the gear was at fishing depth.

for pollock, Atka mackerel, and Pacific cod and SSL population trend. This relationship was uniformly negative as well. Lowered juvenile survival has been indicated as a contributing cause for the SSL decline (York 1994). Though some juveniles are still nursing, the fall months may be critical to juvenile survival in particular. Young SSL begin learning how to forage during this period (Gentry 1970, Sandegren 1970) and readily available prey may be an important dietary supplement for them. Younger, smaller SSL do not travel as far or dive as deeply as older, larger SSL (Loughlin et al. 2003), making the availability of nearshore prey particularly important to them. If growing, juvenile SSL depend entirely on milk for their increasing caloric demands, readily available prey will be extremely important for nursing females. Localized depletions of fish caused by intense fishing activity around SSL rookeries in fall could be deleterious to juvenile SSL survival.

Because mechanisms for fisheries effecting the SSL decline exist, it is natural to ask how much of the SSL decline can be explained by fisheries activities. Statisticians often use the R^2 value to represent the amount of variation in the response variable that can be explained by the predictor variable. Using this interpretation, an R^2 value of 20–30% is not particularly compelling. That is, if differences in the fishing variables around rookeries explain only 30% of the observed difference in SSL population decline, what about the other 70%? However, that interpretation of R^2 can be misleading. To get an idea of the size of the effect quantified by a regression, one must consider both the R^2 and the slope coefficient associated with the predictor variables. The reason for this is that R^2 can be diminished by noise in the data. Even if the "true value" of a variable perfectly predicts the behavior of a response variable, measurement error in either variable can reduce the R^2 value in a regression relating the two. There is no reason to think that the data discussed in this paper are free of noise. The SSL data used are slope estimates based on count data with varying reliability. The fisheries data represent a subset of the total fishing in the area (vessels with observers on board) and have been expanded in a coarse fashion to approximate that total. A lower R^2 value would be expected under these conditions.

How strong is the actual signal? Close examination of plots of fishing variable ranks and SSL population trend (Fig. 8) indicated that the difference in SSL population trend between areas of high fishing intensity and low fishing intensity is meaningful. The average population trend estimate for the 12 sites that had less then 100 fishing events within 0–20 km between 1977 and 1991 is approximately –0.0517 (using the 1977–1991 SSL population trend estimate), while the average for the 20 rookeries which had more than 100 fishing events within 0–20 km is about –0.1187. A decline rate of –0.1187 represents a loss of about 12% of the population per year. At that rate, a population of 100 animals would drop to less than two individuals in 31 years. Compare that to a decline rate of 5% a year, in which the same starting population of 100 animals would take 73 years to fall to under two individuals.

Furthermore, the YFC 1991 trend estimates that are associated with low fishing variable ranks are consistent with the SSL population trend estimates for the years 1991–2001. That means that all SSL rookeries show a post-1991 decline rate that is approximately equal to the decline rate associated with low fishing pressure before 1991.

What might have caused the relationship between fishing and SSL population trend to reverse around 1991? One possible explanation for the positive slope coefficients is that an area of high yield for fisherman

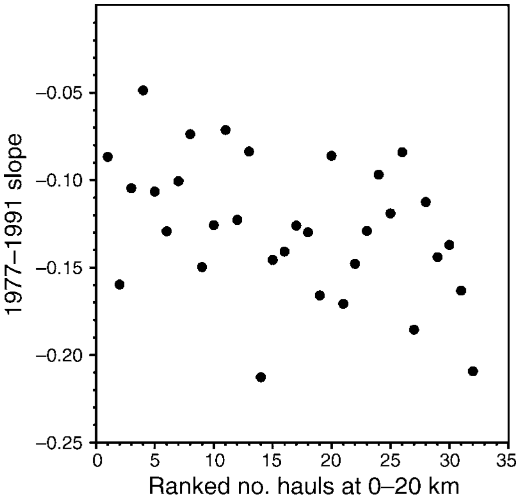

FIG. 8. Ranked number of hauls at 0–20 km from SSL rookeries vs. 1977–1991 SSL population trend estimate.

PLATE 1. Steller sea lion pup. Photo Credit: D. Hennen.

may indicate an extremely rich prey field for SSL. That is, competition was reduced because the resource supply outstripped the needs of both fishery and SSL. In this case, both the SSL and the fisherman would do well in those areas. This would support the hypothesis that the decline of SSL has taken the population below a critical threshold level for exploitative competition with fisheries. That is, the fish resource not removed by the fisheries is enough to satisfy the foraging needs of the remaining smaller population of SSL. Using this analysis, it is impossible to say that a critical SSL population size for exploitation competition does not exist. If a threshold population size exists, restricting the interaction between the fishery and SSL is certainly a good management strategy, if managers wish to restore the SSL population to levels above that threshold.

Other explanations are possible. For example, ongoing climate change has probably altered the composition of the Bering Sea and Gulf of Alaska ecosystems in a way that affected both SSL and the commercial fishery. Trites et al. (*in press*) review the hypotheses relating the SSL decline to climatic regime shifts. These are largely based on the "junk food hypothesis," first suggested by Alverson (1991), who suggests that a decrease in fatty "forage fishes" (thought to be of higher caloric value to SSL) coupled with an increase in the leaner gadid species (which may have a lower caloric value) might have contributed to the SSL decline. The shift to warmer seas that started around 1977 may have favored gadid species (Hollowed et al. 2001). Fritz and Hinckley (2005) however, conducted a critical review of these hypotheses and found little support for linkages between the regime shift and increases in gadid population size or decreases in forage fish populations. They also did not find evidence of the supposed deleterious effects of gadid consumption by wild SSL.

It is impossible, given the data used in this study and the timing of the regime shifts in the area, to conclude that environmental change is not responsible for the patterns seen in this analysis; mainly because there was another regime shift in 1989, which may have again altered the fishery/SSL relationship (Hare and Mantua 2000, Benson and Trites 2002). The mechanism through which the regime shift of 1989 could have slowed the SSL population decline is unclear, however. The regime shift of 1989 did not increase the population sizes of "forage fish," such as herring and Atka mackerel. In fact, it seems to have decreased them (Hare and Mantua 2000). Pollock and large flatfish populations decreased after 1989. These fish eat smaller fish and probably compete with SSL. Reductions in these species however, seem to have started well before 1989 (Hare and Mantua 2000).

There is also the possibility that the pattern relating SSL population decline to fisheries activity is due, not to SSL mortality, but to SSL movement. There is a chance that the declines seen at individual rookeries are the result of animals moving from one rookery to another, rather than animals actually dying. This however, seems unlikely based on both movement studies and genetic analysis (Bickham et al. 1996, Raum-Suryan et al. 2002).

It has also been suggested that killer whale predation might have contributed to the SSL decline (Williams et al. 2004). Killer whale activity might explain the pattern seen in this analysis if fisheries, SSL and killer whales are all attracted to the same area (Fishers and SSL to catch fish, and killer whales to catch SSL). Depletion of SSL through predation might result in better fishing in those areas, thus explaining the pre-1991 pattern. While this explanation fits the pre-1991 pattern, it does not explain the post-1991 situation. Why would killer whales suddenly stop preying on SSL in areas of high fishing activity?

The most parsimonious explanation for the alterations in the relationship between SSL population trend and fishing, are the regulatory changes that went into place in and around 1991.

The links between the regulatory changes put in place in 1991, and the changes in the relationship between SSL and the Bering Sea and Gulf of Alaska fisheries are hard to dismiss. For example, in mid-1990, aggressive enforcement of protective regulations, especially as they relate to the intentional killing of SSL began, and incidental take quotas were reduced. If SSL/human interaction before 1991 frequently led to the death or injury of SSL, then a negative relationship would result from the fact that more interactions occur where more fishing occurs. This relationship would be strongest near shore because SSL would be more likely to be seen near shore since they are arriving at and leaving from the same place repeatedly, whereas off shore they are likely to visit a variety of locations to forage. There is also more opportunity for SSL and fishermen to avoid interactions offshore, since the area concerned (in this analysis, a circle with expanding radius) is much greater. The months of the summer and fall, when SSL are more likely to be found near shore would probably contribute to this pattern as well. Fishermen shot an unknown number of SSL before 1991 and very few are thought to have been shot since (T. R. Loughlin, *personal communication*). This reduction of direct kills alone may have been sufficient to cause a shift in the fishery/SSL relationship from negative to positive.

In 1990, a 3-nautical mile "no-approach" buffer zone was established around important rookeries, and in 1992, trawl fishing within 10 nautical miles (approximately 18 km) was prohibited around 37 rookeries in the GOA and Bering Sea Aleutian Islands (BSAI). Before the establishment of these exclusions, near shore, small trawl vessels produced the strongest negative association with SSL population trend (of any gear type and distance), following the protection, that relationship was no longer significant.

The negative association with small trawl vessels is simple to explain if, as discussed before, the association is due to the fact that more interactions led to more deaths and injuries for SSL, by shooting or incidental catch. Small trawl fishing was the most common gear type employed inside the 0–30 km range during this period, which would indicate that the probability of a small trawl vessel encountering SSL was probably higher than for other gear types. It is also possible that small trawler fishing gear directly killed more SSL than other gear types (Perez and Loughlin 1991). Furthermore, small trawlers may have caused localized depletions of fish populations near rookeries. These aggregations may be critical to the foraging success of lactating females and juveniles.

In 1991, some alterations in the pollock fisheries management plan were implemented. The basic idea behind them was to spread out the pollock catch over time and space (NMFS 2000). This and subsequent changes to the Atka mackerel fisheries management plan (NMFS 2000) may have lead to the changes seen in the seasonal relationship between SSL and fisheries. Before the implementation of these plans, summer and fall fishing showed the strongest negative relationship with SSL population decline. After 1991, summer and fall fishing were unrelated to the SSL decline and winter and spring fishing produced the strongest positive relationship with SSL population trend.

The positive association with offshore fishing after 1991 may simply be an indicator of particularly rich prey fields. That is, an area productive enough to support the needs of both SSL and the commercial fishery. Or it may indicate that the SSL population has dropped below a level where competition with fisheries is a factor. It is important to note however, that SSL continued to decline through 2001. The continuing decline may be due to other factors such as predation by killer whales (Williams et al. 2004), or reduced fecundity (Holmes and York 2003). Fishing no longer appears to be contributing, but it is important to remember that the SSL population is at a depressed level. If their numbers begin to increase, the relationship between fisheries and SSL may change again.

Conclusion

The motivation for this analysis was to examine whether the protective regulations instituted by NMFS around 1991 have helped the SSL population. Those regulations were enforced around all major rookeries in the western stock range. Since there were no sites left unprotected, a comparison between "treatment" and "control" units was not possible. Therefore, a conclusive cause and effect relationship between fishing and SSL population trend cannot be determined. However, the available data on both fishing and SSL comprise a long time series that encompasses several years before and after the enforcement of the SSL protection measures. Thus, while it is impossible to say that some coincident third factor was not responsible for the patterns seen in fishing and SSL population, it is possible to determine whether those patterns changed after the onset of protective measures.

The observed relationship between local SSL population trends and the Bering Sea and Gulf of Alaska fisheries activity around rookeries, in the period before SSL received protection under the ESA in 1991, is different in almost every way measured, from the relationship observed after protections went into place. Although this study cannot rule out alternative hypotheses, the pattern of the relationship, and the pattern of the changes in that relationship, is compatible with the hypothesis that fishery activities in the vicinity of rookeries had a negative effect on SSL populations and that the protections instituted beginning in 1991 have reduced this effect.

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