Central California Gillnet Effort and Bycatch of Sensitive Species, 1990-1998

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Abstract

During the 1980s, extensive bycatch of seabirds and marine mammals in central California's set gillnet fisheries prompted a series of area and depth closures, which ultimately appeared successful at reducing mortality of the species of primary concern, Common Murre *(Uria aalge)*, sea otter *(Enhydra lutris),* and harbor porpoise *(Phocoena phocoena)*. The effects of the restrictions, however, were confounded with changes in the distribution and intensity of fishing effort during the early 1990s. This study documents 1990-1998 patterns of fishing effort in the central California halibut *(Paralichthys californicus)* gillnet fishery and presents information on bycatch of the above three species. A National Marine Fisheries Service observer program obtained bycatch data from 1990 to 1994, but was discontinued after 1994. Since then, gillnet effort has increased and shifted into the southern areas of Monterey Bay, where bycatch was high during the 1980s. The recent increase in gillnet effort coincides with higher beach deposition rates for all three species. In this study, historical entanglement rate data are combined with estimates of fishing effort for 1995-1998 to produce several sets of mortality estimates based on a variety of assump-

tions. Without further data, it is not possible to validate most of the assumptions. The range of total mortality estimates for the 4-year period 1995-1998 is 5,918-13,060 Common Murres (S.E. 477-1,252), 144-662 harbor porpoises (S.E. 18-53), and 17-125 sea otters (S.E. 4-25), raising concern for all three species. The recent changes in fishing effort and distribution underscore the importance of monitoring variability in both fishing practices and the distribution of vulnerable species when evaluating long-term fishery impacts.

Introduction

Central California was an important area for the California halibut *(Paralichthys californicus)* set gillnet fishery during the 1980s. Several species of seabirds and marine mammals were susceptible to entanglement in these nearshore gillnets (Wild 1990), and there was particular concern over populations of Common Murre *(Uria aalge),* southern sea otter *(Enhydra lutris),* and harbor porpoise *(Phocoena phocoena).* At least 70,000 Common Murres died in set gillnets in the 1980s (Takekawa et al. 1990), along with hundreds of sea otters (Wendell et al. 1986), and about 2,000 harbor porpoises (Barlow and Hanan 1995). Concern about bycatch of these species resulted in a series of restrictions on fishing in shallow waters (Wild 1990). In the San Francisco area north of Pigeon Point (Fig. 1), a 73 m (40 fm) depth closure effectively shut down the fishery in early 1987. In the Monterey Bay and Morro Bay areas, a series of depth restrictions was implemented between 1987 and 1990 (Wild 1990), and since 1991 set gillnets in this region have been restricted to waters deeper than 55 m (30 fm).

A National Marine Fisheries Service (NMFS) observer program generated bycatch data for the California halibut set gillnet fishery during 1990-1994, and mortality estimates for this period were published for marine mammals, seabirds, and sea turtles (Julian and Beeson 1998). The observer program was discontinued at the end of 1994, mainly because harbor porpoise mortality was low and coastwide set gillnet fishing effort had declined. Since 1994, this fishery has undergone changes in effort and distribution that potentially affect the three species of concern, Common Murre, sea otter, and harbor porpoise. Because of these changes, previous methods of estimating mortality for central California may no longer be adequate. In this study, we summarize published mortality information for 1990-1994, present detailed information on the 1990-1998 distribution and magnitude of set gillnet fishing effort in central California with emphasis on the Monterey Bay region, and provide a range of mortality estimates for the above three species in the years since 1994. We further evaluate biases in the bycatch estimates, relate levels of mortality to these species' population status, and make recommendations for future monitoring.

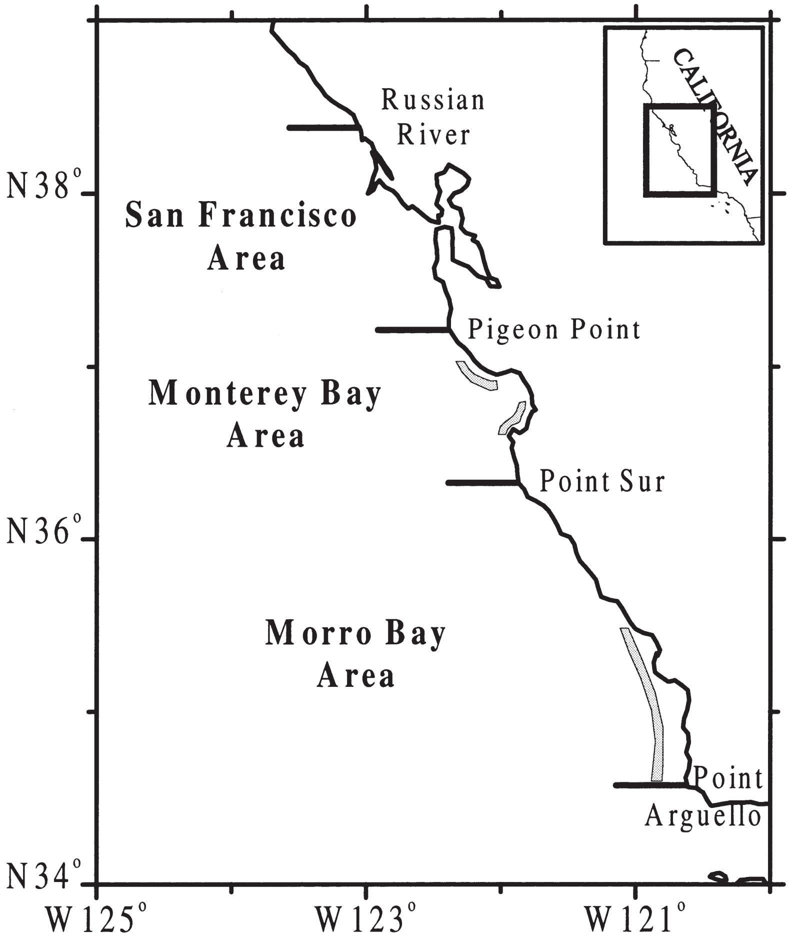

Figure 1. Central California study area and major areas of gillnet fishing activity during the 1980s and 1990s. Shaded areas along sections of the coast correspond to approximate present fishing areas for the strata north Monterey Bay, south Monterey Bay, and Morro Bay.

Methods

Fishery Description

The analyses presented below include data only for the central California halibut set gillnet fishery, which uses gillnets with a mesh size of >21.6 cm. This fishery currently operates year-round between Point Arguello and Pigeon Point (Fig. 1), commonly with a peak in effort between July and October. Typically, each vessel deploys one or more bottom-set gillnets of

Table 1. Data summary for 1987-1990 California Department of Fish and Game (CDFG) and 1990-1994 National Marine Fisheries Service (NMFS) observer programs, restricted to >37 m water depth (as used in analyses E-F).

Data Source		Morro Bay		South Monterey Bay		North Monterey Bay	
CDFG (1987-1990)	Observed sets	0		81		31	
	Entanglements	No.	No./set	No.	No./set	No.	No./set
	Common Murre	–	–	166	2.049	322	10.387
	Harbor porpoise	–	–	15	0.185	11	0.355
	Sea otter	–	–	5	0.062	0	0.000
NMFS (1990-1994)	Observed sets	53		14		242	
	Entanglements	No.	No./set	No.	No./set	No.	No./set
	Common Murre	50	0.943	25	1.786	776	3.207
	Harbor porpoise	0	0.000	3	0.214	14	0.058
	Sea otter	0	0.000	0	0.000	0	0.000

about 914 m length (not to exceed a combined net length of 2,745 m; California Fish and Game Code 8625) for a period of 24-48 hours (see Julian and Beeson 1998 for additional gear details). The number of sets per vessel-day has varied regionally between the Morro Bay area (3.1 sets per day, standard deviation S.D. = 1.1, based on $n = 43$ observed days during 1990-1994) and the Monterey Bay area (1.5 sets per day, S.D. = 0.7, $n = 167$). The overall coastwide average is 3.1 (S.D. = 1.3, $n = 2,587$; Julian and Beeson 1998). At times, vessels set additional nets with smaller mesh sizes targeting fish other than halibut, but these sets are not included in this study.

Effort and Mortality Estimation

The California Department of Fish and Game (CDFG) estimates annual fishing effort, measured as the number of vessel-days fished, by geographic region using vessel logbooks and landing receipts (Diamond and Vojkovich 1990, Julian and Beeson 1998). Effort is assigned to 10×10 minute geographic CDFG blocks whenever possible; unassigned effort is prorated among blocks within the fishing range of the port of landing. Entanglement rates in this study were estimated using data from two observer programs conducted in 1987-1990 and 1990-1994 (Table 1). The primary data source was a 1990-1994 NMFS observer program, which observed about 10% of central California fishing effort. However, very little fishing effort in 1990-1994 took place in the southern portions of Monterey Bay,

Table 2. Summary of mortality estimation analyses. Method A corresponds to Julian and Beeson (1998).

Analysis	Central CA strata	Depth restrictions	Effort unit	Sets/day (Mor, Mry)	NMFS data?	CDFG data?	Observed effort included: Mor	S.Mry	N.Mry
A	None	None	Day	1.8, 1.8	Yes	No	44 days	8 days	163 days
B	Mor, Mry	None	Day	3.1, 1.5	Yes	No	44 days	8 days	163 days
C	Mor, Mry	None	Day	3.1, 1.5	Yes	Yes	44 days	77 days	194 days
D	Mor, S.Mry, N.Mry	None	Day	3.1, 1.5	Yes	Yes	44 days	77 days	194 days
E	Mor, S.Mry, N.Mry	Only >37m	Set	3.1, 1.5	Yes	Yes	53 sets	95 sets	273 sets
F	Mor, S.Mry, N.Mry	Only >37m	Set	3.0, 3.0	Yes	Yes	53 sets	95 sets	273 sets

Key to strata: Mor = Morro Bay, Mry = Monterey Bay

where most effort has taken place since 1995, and therefore these data may not be representative of recent fishing activity. For this reason, the NMFS data were supplemented with data obtained by CDFG in 1987-1990, when about 5% of fishing activity within the Monterey Bay region was monitored.

The basic approach to mortality estimation follows that described by Julian and Beeson (1998) and involves a simple mean-per-unit estimator according to the following equations:

$$\hat{m} = D\hat{r} \quad (1), \qquad \text{and} \qquad \hat{\sigma}_m^2 = D^2\,\hat{\sigma}_r^2 \quad (2),$$

where $\hat{m}$ = total estimated mortality, $\hat{r}$ = estimated number of entanglements per unit effort, D = total fishing effort, $\hat{\sigma}_m^2$ = variance of $\hat{m}$, and $\hat{\sigma}_r^2$ = variance of $\hat{r}$, estimated from the individual effort days as in Julian and Beeson (1998) or from the individual sets using bootstrap sampling methods, depending on the analysis approach used (see below). Previously published mortality estimates for 1990-1994 (Julian and Beeson 1998) did not stratify geographically within central California. In this study, regional differences in entanglement rates were evaluated using an analysis of variance (ANOVA) model of the form $\log(n+1) = \mu + \beta_i x_i + \varepsilon$, where n is the number of observed entanglements, μ is the model mean, β_i is the coefficient for geographic stratum x_i, and ε is a random error term. Based on the ANOVA results for harbor porpoise and Common Murre (too few sea otter entanglements were observed for a meaningful test), we included geographic strata in the analyses below. Mortality for 1995-1998 was estimated using entanglement rate data from previous years, because no observer program data are available after 1994. This is only valid if prior-year data are representative of entanglement rates in the unobserved years and if certain assumptions are met. In this study, six mortality estimation analyses (A-F, Table 2) were performed to bracket the range of potential mortality, given different assumptions relating to the following issues: (1) geographic stratification within central California, (2) choice of prior-year entanglement rate data, (3) depth effects on entanglement rates, and (4) number of sets per day.

Depth Distribution Data

During the 1987-1990 CDFG monitoring program, several depth restrictions were implemented to protect diving seabirds and sea otters, which are more abundant in shallower waters. To reduce potential bias caused by inclusion of CDFG data for shallow depths which may have higher bycatch rates than the current 55 m minimum, we evaluated survey data for Common Murres, sea otters, and harbor porpoises to determine a depth range within which relative abundances are similar and entanglement rates are expected to be comparable. The surveys were conducted in the Monterey Bay region, where the majority of bycatch for these three species has occurred. Common Murre distribution was investigated based on systematic shipboard strip transect surveys conducted monthly in Monterey Bay from May to November 1997-1998 (see Harvey and Benson 1997 for methodology details). The surveys consisted of seven inshore-offshore transects spaced 5.6 km apart and extending from 50 m depth in the southern bay and 30 m depth in the northern bay offshore to 122°5′ W (Fig. 2). The distributions of harbor porpoises and sea otters were evaluated based on sighting and effort data from summer/fall aerial surveys conducted annually in 1988-1991 and biennially from 1993 to 1997 (Forney 1999a). Surveys were flown at 198 to 213 m altitude, zigzagging between the coast and the 92 m isobath (Fig. 3), and all sightings of cetaceans and sea otters were recorded. Only sightings and effort for Beaufort Sea states 0-2 and <25% cloud cover were included in the depth analyses. Transects were divided into 10 m depth intervals (Forney 1988), which were later combined to increase sample sizes. Standardized encounter rates were calculated as the number of animals seen per 100 km surveyed in each depth interval.

Stranding Data

Stranding rates of dead seabirds and marine mammals have been correlated with previous mortality events in central California (Wild 1990) and are provided below for reference. Detailed stranding information was available for the Monterey Bay area from the Monterey Bay National Marine Sanctuary's Beach COMBERS (Coastal Ocean Mammal/Bird Education and Research Surveys) project (Benson et al. 1999). Monthly surveys of the sandy beaches in Monterey Bay (totaling 47.4 km) have been conducted since May 1997 by trained volunteers. All beachcast birds and mammals are recorded, providing a comprehensive record of monthly deposition. For bird specimens, a toe is clipped each month, allowing determination

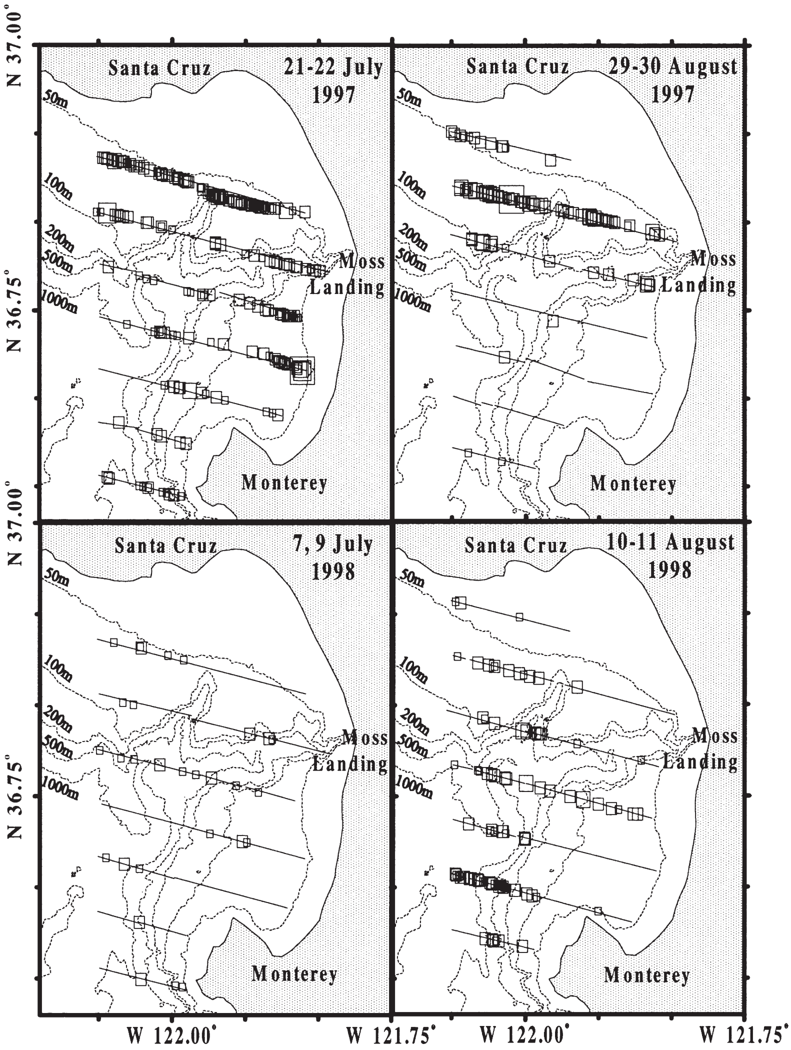

Figure 2. Transect lines surveyed and sighting locations (squares) for Common Murres in July and August 1997-1998. Larger symbols indicate a greater number of individuals per sighting.

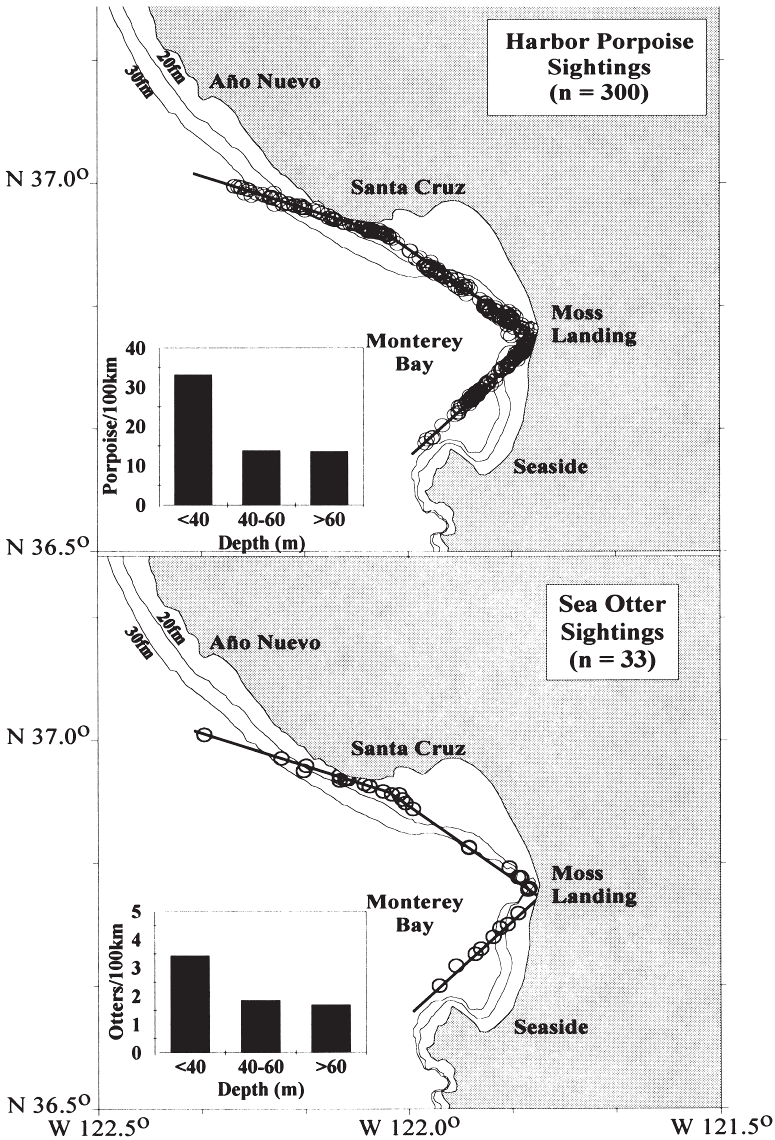

Figure 3. *1986-1997 aerial survey transects (lines) and sighting locations for sea otters and harbor porpoises (for all survey conditions). Bar charts summarize encounter rates (individuals per km) by depth, using only survey effort conducted in good conditions (see text).*

of residence time and the number of newly deposited birds. A similar beach survey was conducted from April 1992 to April 1993 to investigate seabird deposition rates (Mason 1997), and these data are also summarized. Additional coastwide stranding information for marine mammals is compiled by NMFS (for pinnipeds and cetaceans) and by CDFG (for sea otters), based on reports from a network of participating institutions throughout California.

Results

Fishing Effort

From 1990 to 1994, effort in the Monterey Bay area was concentrated in the northern portions of the bay, ranging from 144 to 266 fishing days (Fig. 4). After 1994, gillnet effort in the Monterey Bay area increased to a high of 504 days in 1997, and since 1996 the majority of nets have been set in the southern parts of the bay. In the Morro Bay area, effort dropped from 687 fishing days in 1990 to 179 days after the 55 m depth closure was implemented in 1991 (Fig. 4) and has remained lower in this area through 1998 (range 34-179 days).

Depth Distribution

Visual inspection of Common Murre distribution data from the surveys in Monterey Bay indicates a temporally variable distribution covering both shallow and deep waters (see examples in Fig. 2), with highest densities in the northern bay. Temporal variations in the distribution of Common Murres include changes in depth ranges but are driven primarily by changes in prey availability (Croll 1989, Ainley et al. 1996). Because these patterns appear to be complex and inconsistent between years, we have assumed for analyses A-D that no systematic depth-related differences in entanglement rates are present within the range of observed fishing depths (77% of observed sets occurred at >37 m depth, 22% at 27-36 m depth, and 1% at 18-26 m depth). The 1988-1997 harbor porpoise aerial surveys covered a total of 1,915 km on three Monterey Bay area transects (Fig. 3), yielding 24 sightings of 47 sea otters and 192 sightings of 420 harbor porpoises during good weather. Encounter rates were highest in the <40 m depth category for both harbor porpoises and sea otters (Fig. 3). In waters deeper than 40 m, encounter rates for both species appeared to be relatively constant out to the maximum survey depth of about 92 m.

Mortality Estimates

Because the ANOVA indicated significant differences ($\alpha < 0.05$) in entanglement rates within central California (Table 3), the present study included geographic strata for all analyses except analysis A (which represents previously published estimates that used a single central California stratum).

Table 3. Analysis of variance tests for differences in entanglement rates between potential geographic strata.

Model	Effect	Sum of squares	d.f.	*F*-ratio	Probability
Common Murre					
North vs. south Monterey Bay area	Stratum	4.77	1	4.99	$P = 0.026$
	Error	349.49	366		
Morro Bay area vs. Monterey Bay area	Stratum	29.20	1	37.47	$P << 0.001$
	Error	390.51	501		
Harbor Porpoise					
North vs. south Monterey Bay area	Stratum	0.17	1	2.93	$P = 0.088$
	Error	21.56	366		
Morro Bay area vs. Monterey Bay area	Stratum	0.43	1	9.66	$P = 0.002$
	Error	22.21	501		

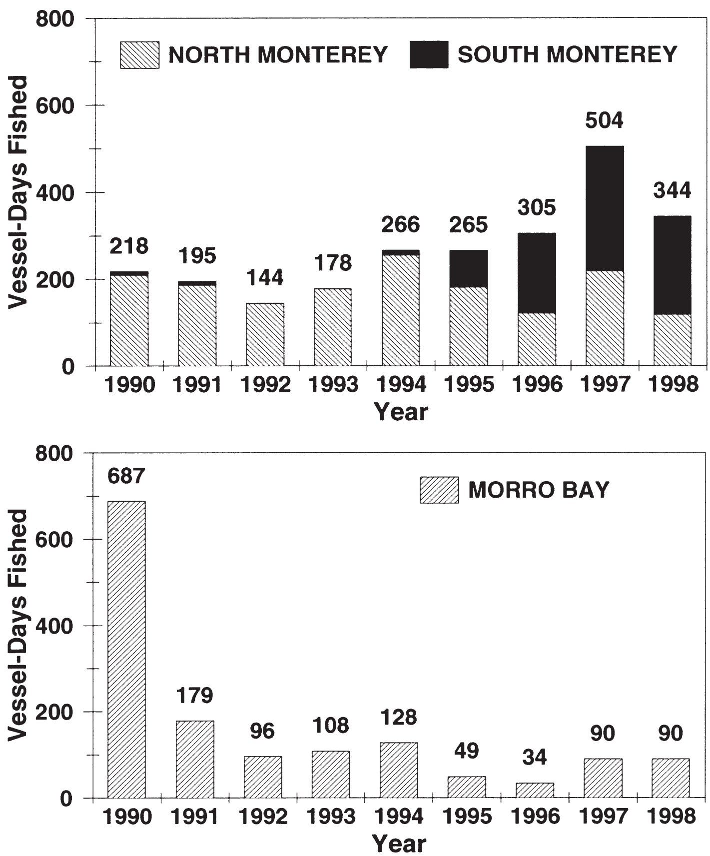

Figure 4. Fishing effort by region for the 1990-1998 central California halibut set gillnet fishery.

Only analysis methods A and B were performed for 1990-1994, because year-specific entanglement rates were available for those years. For the unobserved years (1995-1998), methods C-F included different combinations of prior-year entanglement rate data and geographic strata. Analyses A-D included all observed fishing depths, as in Julian and Beeson (1998). Analyses E-F included only entanglement rate data for >37 m, to minimize potential depth-related bias while maintaining the largest possible sample size. The six analysis options yield a range of mortality estimates (Table 4); in all cases, estimates are highest in 1997 because of the increase in total effort in the Monterey Bay area. Without additional data to evaluate the assumptions of these six analyses, no single estimate can be considered the most accurate; however, the stratified analyses are expected to be more accurate than the unstratified analysis (A).

Other seabird and marine mammal species observed entangled during the 215 days (391 sets) of fishing effort monitored in central California during 1990-1994 (Julian and Beeson 1998) include two Double-crested Cormorants *(Phalacrocorax auritus),* one Pacific Loon *(Gavia pacifica),* six unidentified alcids, three unidentified cormorants, 101 California sea lions *(Zalophus californianus),* 44 harbor seals *(Phoca vitulina),* and 18 northern elephant seals *(Mirounga angustirostris).* Because these levels of mortality are low in relation to the estimated population sizes (Barlow et al. 1997, McChesney et al. 1998), they are not presently a management concern and therefore no mortality analyses were performed for these species.

Beach Deposition and At-sea Sighting Distributions

Beach deposition of Common Murres peaked during the summer months of both 1997 and 1998, with a sharp, short-lived peak in August-September 1997 and a broader peak in May-August 1998 (Fig. 5). In 1997, Common Murres dominated the deposition, whereas in 1998 a wide variety of other species was found (Benson et al. 1999). In both summers, deposition was distinctly higher than during the same period in 1992-1993 (Mason 1997), when no gillnet fishing took place in the inner areas of Monterey Bay (Fig. 4). Although there is no direct evidence linking the increased deposition to gillnet fisheries, there is reason to suspect that gillnets were at least in part responsible for the observed mortality, particularly in 1997. At-sea survey data in the Monterey Bay region indicate that Common Murres were abundant in the southern bay fishing areas (Fig. 2) during the time of peak fishery landings in July-August and just prior to the August-September peak in deposition (Fig. 5). Although Common Murres were also abundant in the northern parts of the bay, 82% (541/656) of the beachcast specimens were deposited on a 14 km section of beach facing the southern areas of gillnet fishing activity. Furthermore, deposited Common Murres were not young-of-the-year and showed no obvious signs of emaciation. In 1998, Common Murres were much less abundant in the areas of gillnet

Table 4. Estimates of mortality for Common Murre, sea otter, and harbor porpoise in the 1990-1998 central California halibut set gillnet fishery, based on six analysis approaches (A-F, see Table 2).

Analysis	Estimated Mortality (standard error in parentheses)								
	1990	1991	1992	1993	1994	1995	1996	1997	1998
Common Murre									
A	1,300 (273)[a]	2,201 (594)	2,333 (653)	879 (281)	284 (82)	1,319 (210)	1,424 (226)	2,500 (398)	1,830 (291)
B	2,104 (658)	1,148 (326)	1,388 (423)	560 (196)	218 (64)	1,366 (219)	1,531 (249)	2,597 (416)	1,824 (288)
C	Not applicable					1,355 (256)	1,519 (293)	2,576 (488)	1,810 (336)
D						1,326 (246)	1,178 (205)	2,064 (353)	1,350 (229)
E						1,415 (297)	1,332 (280)	2,263 (475)	1,527 (321)
F						2,824 (593)	2,663 (559)	4,525 (950)	3,048 (640)
Harbor porpoise									
A	37 (21)[a]	38 (18)	48 (22)	13 (8)	14 (13)	27 (7)	29 (8)	51 (14)	37 (10)
B	42 (26)	20 (10)	29 (14)	8 (6)	11 (10)	28 (8)	32 (9)	54 (15)	37 (10)
C	Not applicable					42 (8)	48 (9)	80 (15)	56 (11)
D						43 (8)	56 (14)	92 (21)	66 (17)
E						49 (9)	69 (13)	113 (21)	80 (15)
F						97 (18)	137 (26)	227 (43)	161 (31)
Sea otter									
A	27 (14)[a]	0 (-)	0 (-)	0 (-)	0 (-)	5 (3)	5 (3)	9 (5)	6 (4)
B	64 (36)	0 (-)	0 (-)	0 (-)	0 (-)	3 (2)	2 (1)	6 (3)	6 (3)
C	Not applicable					7 (3)	7 (3)	14 (5)	11 (4)
D						8 (3)	12 (5)	21 (8)	18 (7)
E						7 (3)	14 (6)	24 (11)	18 (8)
F						13 (6)	29 (13)	47 (21)	36 (16)

[a] Julian and Beeson (1998) estimated 1990 mortality only for July-December.

Analysis A includes 1990-1994 mortality estimates from Julian and Beeson (1998) and follows their methodology (using 1990-1994 entanglement rates) for 1995-1998.

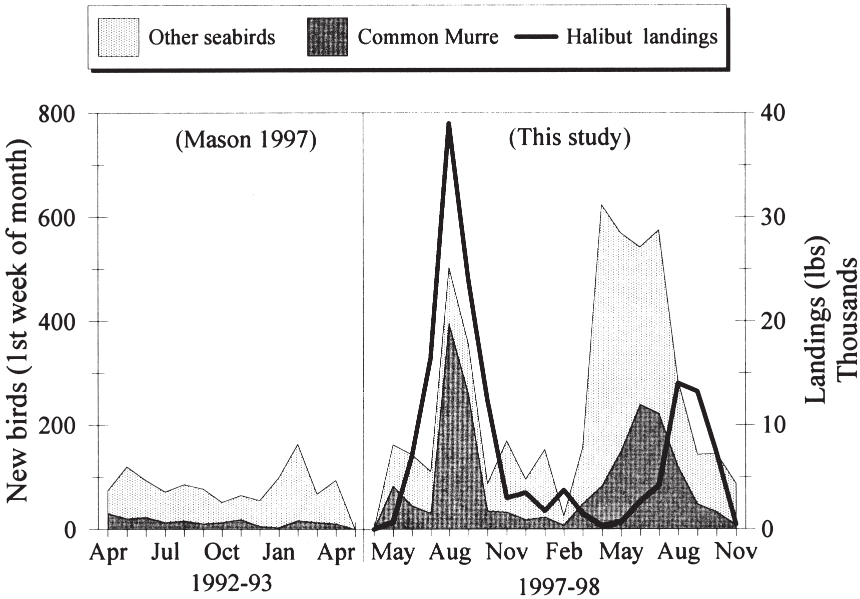

Figure 5. Monthly beach deposition of seabirds in Monterey Bay, May 1997-November 1998. Halibut landings in the Monterey Bay area for the same period and similar beach deposition data for 1992-1993 are also shown for comparison.

fishing during the summer halibut landing peak (Figs. 2 and 5), suggesting that fewer birds were susceptible to entanglement in that year.

Harbor porpoise stranding rates are available only for the entire California coast, but the majority of stranded individuals were found in the Monterey Bay area (NMFS, unpublished data). Sea otter stranding data have been summarized coastwide and separately for the Monterey Bay area (north of Pt. Sur). Strandings for both species have increased in recent years (Table 5). Harbor porpoises are known to be common in Monterey Bay in the areas where gillnet fishing has increased (Forney 1999a). The 1988-1997 aerial survey data (Fig. 3) also indicate that sea otters occur in waters deeper than 55 m, particularly in southern Monterey Bay. Although sea otter sighting efficiency is reduced at the altitudes flown during these porpoise surveys, the recorded sightings represent a minimum number present and should not exhibit any distributional bias within open waters. A recent low-altitude sea otter survey extending out to 92 m depth also recorded about 10% (9/93) of the sightings in Monterey Bay in water depths >55 m (J. Ames, CDFG, Santa Cruz, unpubl. data).

Table 5. California strandings of dead harbor porpoises and sea otters in 1990-1998.

Species	Number of stranded individuals reported								
	1990	1991	1992	1993	1994	1995	1996	1997	1998
Harbor porpoise	17	11	8	4	8	16	18	26	37
Sea otter									
Total	–	78	110	126	128	160	179	152	213
Monterey Bay area	–	45	53	77	64	99	84	75	136

Discussion

In this paper, we have attempted to evaluate the effects of several assumptions on mortality estimates. Combined, the estimates in Table 4 provide a range of likely mortality during the period 1995-1998. Within each estimation method, however, uncertainty is probably underestimated, because total annual fishing effort has been assumed to be known without error, as in Julian and Beeson (1998). While this is clearly not the case, no data are available to quantify this likely source of error as part of the variance estimate.

The use of a single central California stratum by Julian and Beeson (1998) required one of two assumptions to be true: (1) entanglement rates are the same in all areas of central California, or (2) the proportion of observed effort is the same as the proportion of total effort in each area. Neither of these assumptions appears to be valid. Entanglement rates for 1990-1994 did differ between the Morro Bay and Monterey Bay areas (Table 3), and no fishing trips could be observed in the Morro Bay area during 1992-1993, while 42% of the effort occurred there in those years. Thus Julian and Beeson (1998; Analysis A this study) probably overestimated 1990-1994 mortality for harbor porpoises and Common Murres, because both were more frequently observed entangled in the Monterey Bay area. Our stratified analysis B should provide more accurate estimates of 1990-1994 mortality for these species. Analyses C-F also include geographic strata for central California (Table 2), which should make the mortality estimates more accurate, but less precise, because sample sizes within each stratum are smaller.

Assumptions for 1995-1998 Mortality Estimates

A number of additional assumptions and caveats are relevant to the interpretation of the 1995-1998 analysis results. First, present fishing restrictions require gillnets targeting halibut to be set in at least 55 m of water, but both the NMFS and CDFG observer program data included some effort in shallower waters. Previous mortality estimates (Julian and Beeson 1998) included all observed depths, and the same approach was used in our analyses A-D. However, if densities of Common Murres, sea otters, or harbor porpoises are higher in shallower waters and entanglement rates are proportional to density, this could result in an overestimation of mortality. The observed depth distribution during aerial and shipboard surveys (Figs. 2 and 3) indicated that relative abundances of sea otters and harbor porpoises were similar in 40-60 m and >60 m depth, but higher in waters shallower than 40 m. Therefore, analyses A-D might be expected to have an upwards bias, and analyses E-F would be more accurate. However, mortality estimates for analyses A-D are in fact lower than those for analyses E-F, suggesting that depth-related bias in entanglement rates is absent or trivial.

A second assumption relates to the absolute abundance of Common Murres, harbor porpoises, and sea otters in the areas of gillnet fishing activity. If entanglement rates are related to abundance, then prior-year data will only be representative of present entanglement rates if abundance has not changed substantially. Harbor porpoise abundance estimates have been variable, but no trends are apparent (Forney 1999a,b). Sea otters increased from about 1,500 animals in the late 1980s to nearly 2,400 animals in 1995 before declining again to about 2,100 otters in 1998 (U.S. Fish and Wildlife Service 1997, unpubl. data). Sea otter entanglement rates therefore may have increased. Similarly, central California Common Murre abundance has slowly increased between 1987 and 1997 (McChesney et al. 1998) as the population recovered from a decline in the 1980s. The potential effects of these population increases on entanglement rates are difficult to assess because they also depend on the distribution of the animals with respect to the fishery, which is not known. Therefore, our analysis does not include a correction factor for increases in population size, and mortality for Common Murres and sea otters may be underestimated.

A final assumption is related to the measure of effort and the number of nets set per fishing day. The use of a fishing day as the unit of effort in analyses A-D requires the assumption that daily entanglement rates are constant, without explicit assumptions about the number of sets per day. In analyses E-F, individual nets set in <37 m water depth were excluded, requiring the unit of effort to be changed from fishing days to sets and the number of sets per day to be estimated. In analysis E, we used the mean values observed during 1990-1994 (1.5 and 3.1 sets per day, respectively, for Monterey Bay and Morro Bay). In analysis F, a value of 3.0 sets per day was assumed based on anecdotal information that fishermen tend to set three nets of 914 m length each to achieve the maximum daily net length allowed by law, 2,745 m (California Fish and Game Code 8625). Insufficient information is available regarding the details of the fishery in 1995-1998 to evaluate fishing practices and the true number of sets per day during these years, but analyses E and F encompass a likely range of values.

Species Implications

During the 1990s, gillnet mortality of Common Murres averaged in the low thousands of birds per year. This is lower than levels observed in the 1980s (averaging about 10,000 per year; Takekawa et al. 1990), but still may be affecting this species' recovery. Between 1980-1982 and 1986, the central California breeding population declined from about 229,080 to 108,530 individuals as a result of gillnet mortality, El Niño effects, and oil spills (Takekawa et al. 1990), then remained stable until the early 1990s (Ainley et al. 1994) when it began to show signs of recovery (McChesney et al. 1998). The effect of continued gillnet mortality on central California Common Murres therefore may not be a population-level concern. However, the Devil's Slide and Castle/Hurricane Complex breeding colonies, which disappeared and severely declined, respectively, in the 1980s (Takekawa et al. 1990), have not recovered despite considerable restoration efforts (McChesney et al. 1998, 1999). These two southern colonies are closest to Monterey Bay, and gillnet mortality may play a role in the lack of recovery at these sites.

The range of mortality estimates for harbor porpoise in the 1995-1998 central California halibut gillnet fishery (144 to 622 animals during the 4-year period) represents 2.5%-10.9% of the current population estimate of 5,732 (CV=0.39; Forney 1999b), or an average of 0.6%-2.7% per year. Average estimated mortality in 1995-1998 is higher than during the early 1990s, but lower than estimates for the 1980s (Barlow and Hanan 1995). Most mortality estimates for 1995-1998 exceed the potential biological removal (PBR) of 42 animals per year allowed under the Marine Mammal Protection Act (Forney et al. 1999), in some cases by a factor of two to four. These levels of mortality may not be sustainable for the central California harbor porpoise population. Stranding rates of dead harbor porpoises also doubled in California between 1990-1994 and 1995-1998 (Table 5), coincident with the expansion of the set gillnet fishery in the Monterey Bay region.

Estimated total mortality for sea otters in 1995-1998 (17-125 animals during the 4-year period) ranges from 0.7%-5.3% of the 1995 peak population count of 2,377 individuals (U.S. Fish and Wildlife Service 1997), or an average of 0.3%-1.3% per year. Clearly, the recent changes in the distribution of set gillnet fishing effort are of concern for this population, which is federally listed as threatened under the Endangered Species Act. Sea otter population counts declined from 2,377 to 2,114 animals between 1995 and 1998, and average stranding rates of dead sea otters increased by about 50% between 1990-1994 and 1995-1998 (Table 5). It is likely that gillnet mortality is at least in part responsible for the documented population decline, particularly since sea otters are found beyond 55 m depth in areas of gillnet fishing (Figs. 1, 3). Monitoring of gillnets set in the Monterey Bay region is imperative for an accurate assessment of sea otter mortality in this fishery. More detailed surveys of the distribution of sea otters in the depth ranges and areas of gillnet fishing will also help shed light on the number of otters susceptible to entanglement.

Conclusions

There are many uncertainties in the mortality estimates presented in this study, but the high levels of estimated mortality raise concern. The results underscore the difficulties of managing vulnerable species when potential mortality sources such as gillnets are not monitored. Both fishing practices and the distribution of potentially entangled species can change dramatically between years, and it is therefore not valid to assume that patterns for any given year will be duplicated in future years. In the case of the central California halibut gillnet fishery, harbor porpoise mortality was low and sea otter mortality was thought to be zero in 1994, when the NMFS observer program was discontinued. However, the fishery subsequently underwent changes in distribution and effort, and these changes were not detected until 1997, when a large increase in Common Murre deposition on southern Monterey beaches was documented. Furthermore, the 55 m depth closure implemented in 1991 to protect the southern sea otter was assumed to be effective, but was never actually put to the test in southern Monterey Bay because fishing virtually ceased in that area after the closure (Fig. 3). Given that sea otters are present in these areas, it is likely that they were susceptible to gillnet mortality during 1995-1998.

A sound approach to monitoring species that are vulnerable to human-caused mortality requires some level of continued monitoring of potential mortality sources, such as gillnet fisheries. The halibut gillnet fishery is only one of the gillnet fisheries that operate in this area; other, smaller-mesh gillnet fisheries may also entangle seabirds and, to a lesser extent, marine mammals. In general, observer programs provide the most reliable data, but they are costly to implement. Because of concern over bycatch of harbor porpoise, the NMFS Southwest Region initiated a Monterey Bay area observer program in April 1999 to evaluate the effects of present fishing patterns. Preliminary data indicate that all three species of concern have been observed entangled and bycatch rates are within the range of those estimated in this study. This observer program will provide important new information for understanding bycatch patterns and determining ways to reduce bycatch in the future. Systematic monitoring of beachcast marine birds and mammals has also been demonstrated to provide valuable information during gillnet-related mortality events (Salzman 1989), particularly when combined with shipboard or aerial surveys that shed light on the distribution of animals at sea. Information on temporal and geographic patterns of fishing effort should also be documented on an ongoing basis whenever possible. Only with such comprehensive information will the agencies concerned with the management of sensitive species be able to evaluate the effects of changing fishing practices and quickly address problem situations.

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Seabird Bycatch

Trends, Roadblocks, and Solutions

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