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HOOK EFFECTS ON SEABIRD BYCATCH IN THE UNITED STATES ATLANTIC PELAGIC LONGLINE FISHERY

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ABSTRACT

Recent studies suggest that use of circle hooks can reduce the incidental mortality of some marine fishes and sea turtles in longline fisheries. Analysis of data from the US National Marine Fisheries Service Pelagic Observer Program (POP) revealed a significant hook effect on seabird bycatch. Our analysis focused on the three areas with highest seabird bycatch, the northeast US coast (60°W–71°W, 35°N–42°N), the Middle Atlantic Bight (71°W–82°W, 35°N–41°N), and the South Atlantic Bight (71°W–82°W, 30°N–35°N). We developed two generalized linear models to examine effects of four hook treatments, i.e., four combinations of hook type and size (8/0 J-hook, 9/0 J-hook, 16/0 circle hook, and 18/0 circle hook), on: (1) the probability of catching seabirds on a set and (2) the positive catch rate (i.e., number of seabirds per 1000 hooks in longline sets with at least one seabird caught). Results indicated that combinations of hook type and size significantly influenced the probability of catching seabirds in the United States Atlantic pelagic longline fishery. Use of the 8/0 J-hook led to the highest probability of catching a seabird. Use of circle hooks may significantly reduce seabird bycatch in the US Atlantic pelagic longline fishery, but its effectiveness may be confounded by other factors such as bait type, fishing location, season, and target species. Results of our study were limited by the small number of seabird captures in the POP data.

Seabird conservationists agree that the incidental mortality in longline fisheries is a serious global concern (Brothers et al. 1999a, Tasker et al. 2000, Belda and Sanchez 2001, Furness 2003). The World Conservation Union suggests that longline fisheries affect 61 seabird species, 25 of which are threatened partially due to incidental mortality associated with longline fisheries (FAO 1998, Brothers et al. 1999a). The population declines of several albatross species (Diomedeidae) and other species in the order Procellariiformes are partially caused by longline fishing (Croxall et al. 1982, Brothers et al. 1999a, Tasker et al. 2000, Belda and Sanchez 2001, Furness 2003).

Biological characteristics of seabirds, including late maturity, low reproduction rate, and maternal care of chicks, make their populations vulnerable to incidental mortality from all fisheries. Direct mortality of seabirds in longline fisheries occurs primarily when they are hooked or entangled and are drowned as hooks sink, which may also cause the indirect mortality of chicks if one or both parents are killed (Brothers et al. 1999a, Gilman 2001).

The US Atlantic pelagic longline fishery primarily targets tunas (*Thunnus* spp.) and swordfish (*Xiphias gladius* Linnaeus, 1758), and secondarily targets dolphinfish (*Coryphaena hippurus* Linnaeus, 1758), and sharks (Selachimorpha). Prior to August 2004, two types of hooks, i.e., the J-hook and the circle hook, were used in this fishery. Starting in August 2004, exclusive circle hook use was legally mandated to reduce sea turtle bycatch (69 Fed. Reg. 40734). Recent studies suggest that use of circle hooks can reduce the mortality and injury rate of some marine fishes, sea turtles, and marine mammals and thereby increase their survival after being released (Watson et al.

2005, Serafy et al. 2009). Whether the use of circle hooks will reduce seabird bycatch is undetermined. The present study evaluated a hook effect with four treatments, i.e., four combinations of hook type and size (8/0 J-hook, 9/0 J-hook, 16/0 circle hook, and 18/0 circle hook), as well as other factors that may confound determination of the hook treatment effect on seabird bycatch in the US Atlantic pelagic longline fishery.

Methods

Fishing activities of the US Atlantic pelagic longline fishery are monitored by the National Marine Fisheries Service Pelagic Observer Program (POP). In the POP, randomly selected fishing trips are observed, and information about target catch, bycatch, fishing effort, fishing tactics, and environmental conditions are recorded. POP data from 1992 to 2009 included 11,124 longline sets. Of those, only 66 sets captured a total of 132 seabirds. Because 96% of the observed seabird captures occurred in three areas (Table 1, Fig. 1), the northeast US coast (60°W–71°W, 35°N–42°N), the Middle Atlantic Bight (71°W–82°W, 35°N–41°N), and the South Atlantic Bight (71°W–82°W, 30°N–35°N), and all seabirds were caught on 8/0 J-hooks, 9/0 J-hooks, 16/0 circle hooks, and 18/0 circle hooks, we confined our analyses to these three areas and these four hook treatments.

Because the data set contained a high proportion of zero observations, we examined the effects of the hook treatment factor on seabird bycatch in two steps: (1) we constructed a generalized linear model (Eq. 1) with an assumption of a binomial distribution to examine the hook treatment effect on the probability of catching seabirds; and (2) we developed a generalized linear model (Eq. 2) to analyze the hook treatment effect on the positive catch rate (number of seabirds per 1000 hooks in longline sets that caught at least one seabird) by assuming a lognormal distribution (Lo et al. 1992, Fletcher et al. 2005):

$$\ln\left(\frac{\hat{p}}{1-\hat{p}}\right) = \beta_0 + \sum \beta_j X_j, \quad \text{(Eq. 1)}$$

$$\ln(\hat{c}) = \alpha_0 + \sum \alpha_j X_j, \quad \text{(Eq. 2)}$$

where $\hat{p}$ and $\hat{c}$ are the estimated probability of catching seabirds and the estimated positive catch rate, respectively; β_0 and α_0 are intercepts, β_j and α_j are parameters for the *j*th explanatory variable X_j. This modeling approach is consistent with the delta model that has long been applied to fishery data with a high percentage of zero observations (Lo et al. 1992, Stefansson 1996, Frisk et al. 2002, Maunder and Punt 2004, Fletcher et al. 2005).

In model development, 16 explanatory variables (Table 2) were considered for variable selection through a stepwise approach. Selection was based on the Akaike Information Criterion (AIC) and a chi-square test (Akaike 1974, Burnham and Anderson 2002). At each step in the variable selection process, the variable that reduced the AIC value most or yielded the most significant effects on the response variable was added to the model, repeating the selection process until no substantial improvement was obtained from including an additional explanatory variable. Two-way interactions were not included in the models because they either were insignificant or were correlated with the main factors.

To isolate the hook treatment effect on seabird bycatch, we applied a commonly used approach in catch rate analyses, the catch rate standardization (Maunder and Punt 2004). Specifically, we tested for a hook treatment effect while fixing the values of all the other explanatory variables in the model to their means (continuous variables) or weighted means (categorical variables). Season and bait have been documented to play important roles in catching seabirds in longline fisheries (Klaer and Polacheck 1998, Brothers et al. 1999b, Jimenez et al. 2010, Foster et al. 2012), and target species embodies information about gear configuration and fishing tactics; therefore, we also applied the catch rate standardization approach to examine the effects of these three factors.

Table 1. Analyzed longline sets by hook treatment factor for each fishing area, year, and target species. NEC = the northeast US coast (60°W–71°W, 35°N–42°N), MAB = the Middle Atlantic Bight (71°W–82°W, 35°N–41°N), SAB = the South Atlantic Bight (71°W–82°W, 30°N–35°N). MIX = mixed species, SWO = swordfish (*Xiphias gladius*), TUN = tuna (Scrombidae), SHX = shark (Selachimorpha), YFT = yellowfin tuna [*Thunnus albacares* (Bonnaterre, 1788)], BET = bigeye tuna [*Thunnus obesus* (Lowe, 1839)], DOL = dolphinfish (*Coryphaena hippurus*).

	Sets deployed					Sets with seabirds caught				
	8/0 J	9/0 J	16/0 circle	18/0 circle	Total	8/0 J	9/0 J	16/0 circle	18/0 circle	Total
Area										
NEC	86	113	19	199	417	12	4	0	1	17
MAB	179	182	170	305	836	8	0	3	1	12
SAB	82	193	21	99	395	1	3	0	1	5
Year										
1992	0	21	0	0	21	0	0	0	0	0
1993	0	38	0	0	38	0	0	0	0	0
1994	8	30	0	0	38	0	0	0	0	0
1995	23	11	0	0	34	3	0	0	0	3
1996	32	17	0	0	49	0	0	0	0	0
1997	57	31	0	0	88	8	3	0	0	11
1998	21	68	16	0	105	1	1	0	0	2
1999	26	55	0	0	81	1	0	0	0	1
2000	41	66	0	0	107	0	0	0	0	0
2001	28	62	0	0	90	0	3	0	0	3
2002	26	37	0	0	63	5	0	0	0	5
2003	69	39	0	0	108	1	0	0	0	1
2004	16	13	10	33	72	2	0	0	0	2
2005	0	0	39	76	115	0	0	0	1	1
2006	0	0	12	137	149	0	0	0	2	2
2007	0	0	37	88	125	0	0	0	0	0
2008	0	0	43	120	163	0	0	0	0	0
2009	0	0	53	149	202	0	0	3	0	3
Target species										
MIX	190	117	73	253	633	17	1	0	3	21
SWO	81	197	24	232	534	3	0	1	0	4
TUN	37	90	71	102	300	0	1	2	0	3
SHX	0	3	0	3	6	0	0	0	0	0
YFT	18	33	15	13	79	0	3	0	0	3
BET	17	42	17	0	76	0	0	0	0	0
DOL	4	6	10	0	20	1	2	0	0	3
Grand total	347	488	210	603	1,648	21	7	3	3	34

Results

J-hooks were predominantly used prior to August 2004 and were prohibited thereafter; circle hooks (especially 18/0 circle hooks) were applied more frequently in the northeast US coast and Middle Atlantic Bight areas than in the South Atlantic Bight area, and in targeting mixed species, swordfish, and tunas than in targeting other fish species (Table 1). In the present study, 1648 longline sets were analyzed, of which only 34 sets caught 77 birds. Of the longline sets that we analyzed, 18/0 circle hooks were most frequently used (36%), followed by 9/0 J-hooks (30%), 8/0 J-hooks (21%), and

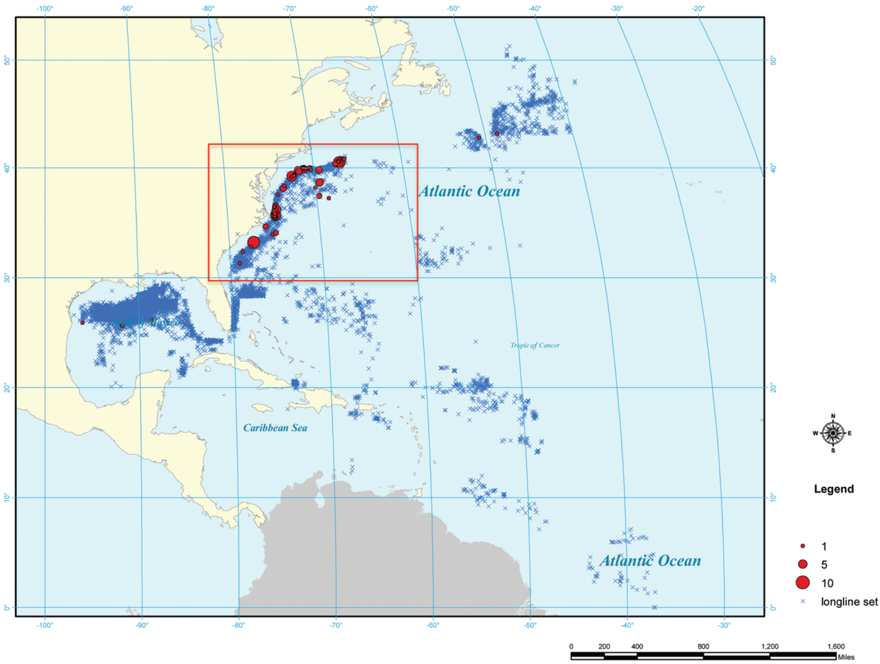

Figure 1. Spatial distribution of longline sets (×) and seabird bycatch (red circles indicate number caught) in the US Atlantic pelagic longline fishery, 1992–2009. The rectangle on the map outlines the three areas with the highest seabird bycatch, i.e., the northeast US coast (60°W–71°W, 35°N–42°N), the Middle Atlantic Bight (71°W–82°W, 35°N–41°N), and the South Atlantic Bight (71°W–82°W, 30°N–35°N).

Table 2. List of explanatory variables tested for significance in model development.

Variables	Notations	Type	Categories/mean
Bait type	BAIT	Categorical	Mackerel, squid
Haul time	HTIM	Categorical	Daytime (same as set time), nighttime
Hook treatment	HOOK	Categorical	8/0 J, 9/0 J, 16/0 circle, 18/0 circle
Season	SEA	Categorical	Spring, summer, fall, winter
Set time[a]	STIM	Categorical	Daytime (6:30–19:30 spring, 5:30–19:30 summer, 7:00–18:30 fall, 7:30–18:00 winter), nighttime
Target species	TAR	Categorical	Mixed, swordfish, tuna, shark, yellowfin, bigeye, dolphinfish (as defined in the POP data set)
Year	YEAR	Categorical	1992–2009
Haul duration (hrs)	HDUR	Continuous	6.6
Latitude (°N)	LAT	Continuous	29.1 (beginning of set)
Longitude (°W)	LON	Continuous	–78.7 (beginning of set)
Bottom depth (km)	BDEP	Continuous	2.1 (maximum depth)
Hook depth (m)	HDEP	Continuous	54.4 (maximum depth)
Number of hooks	NUMH	Continuous	684.1
Set duration (hrs)	SDUR	Continuous	3.7
Set speed (knt)	SPED	Continuous	7.3
Soak duration (hrs)	SOAK	Continuous	8.7

a: time of setting a longline

Table 3. List of seabird species captured by hook treatment. The family total is bolded.

	J-hook		Circle hook		
Species	8/0	9/0	16/0	18/0	Total
Shearwater (Procellariidae)					**12**
Greater Shearwater (*Puffinus gravis*)	0	7	2	1	10
Cory's Shearwater (*Calonectrisdiomedea*)	0	0	0	1	1
Other Procellariidae	0	0	0	1	1
Gannet (Sulidae)					**3**
Northern Gannet (*Morus bassanus*)	0	0	3	0	3
Gull (Laridae)					**13**
Herring Gull (*Larus argentatus*)	0	0	0	1	1
Other Laridae	12	0	0	0	12
Unidentified species	37	12	0	1	**49**
Total	49	19	5	4	77

16/0 circle hooks (13%). Of the captured seabirds, 64% were hooked on 8/0 J-hooks, 25% on 9/0 J-hooks, 6% on 16/0 circle hooks, and 5% on 18/0 circle hooks (Table 3).

Of the 1648 longline sets analyzed, 269 sets (16%) used squid bait and 1373 sets (83%) used mackerel bait. A total of 12 seabirds (16%) were caught on sets using squid bait, and 65 seabirds (84%) were caught on sets using mackerel bait.

Only 36% of the captured seabirds were identified to at least the family level. Gulls (*Larus* spp., in the family Laridae) were the most frequently captured, followed by shearwaters [Procellariidae, especially Greater Shearwater, *Puffinus gravis* (O'Reilly, 1818)], and the Northern Gannet [*Morus bassanus* (Linnaeus, 1758), in the family Sulidae]. J-hooks captured 12 times as many gulls and 1.4 times as many shearwaters as circle hooks.

The highest probability (0.8% on average) of catching seabirds was with the 8/0 J-hook, followed by the 9/0 J-hook (0.3% on average), while the probability of catching seabirds with 16/0 and 18/0 circle hooks was low (0.2% and 0.01% on average, respectively; Fig. 2). Targeting dolphinfish (Fig. 3A) or fishing in the winter (Fig. 3B) had a higher probability of catching seabirds than targeting other species or fishing in other seasons, respectively. Higher positive catch rates of seabirds were obtained when fishing with mackerel bait than with squid bait (Fig. 3C).

The model for estimating the probability of catching seabirds identified the hook treatment effect to be significant (P = 0.002, Table 4). The model for estimating the positive catch rate selected bait type as a significant factor (P = 0.002). Besides the hook treatment effect, the variables year, target species, longitude, and season showed significant effects on the probability of catching seabirds.

Discussion

Our model results indicate a decrease in the probability of catching seabirds when using the 16/0 and 18/0 circle hooks in the US Atlantic pelagic longline fishery. We expected a significant hook treatment effect on the positive catch rate given that different seabird species may have different bill, nape, or body sizes; however, we did not detect any significant hook treatment effect on the positive catch rate, which may be due to the relatively few seabird captures in the data set.

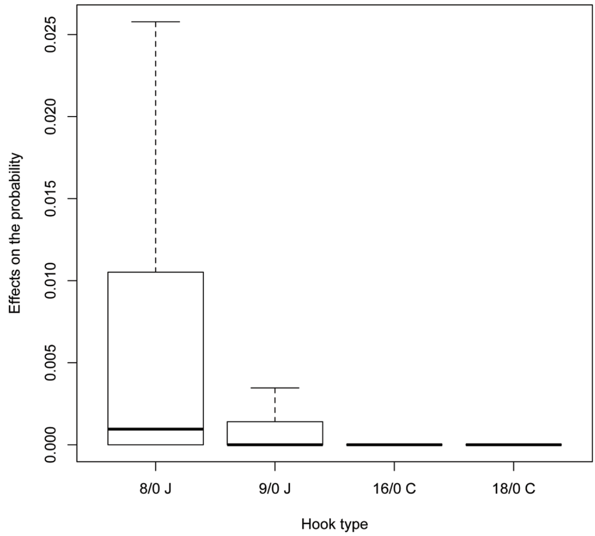

Figure 2. Hook treatment effect on the probability of catching seabirds. J = J-hook, C = circle hook. In a box plot, the bolded line in the middle of a box represents the median; the upper and lower boundaries of a box represent the third and first quartiles; and the upper and lower bars outside a box indicate the range.

The importance of spatial and temporal influences on seabird bycatch in longline fisheries has been previously documented (Klaer and Polacheck 1998, Brothers et al. 1999b, Jimenez et al. 2010). We hypothesize that the spatial patterns in observed seabird bycatch and the seasonal patterns in the probability of catching seabirds can be attributed more to relative seabird abundance in the study areas than to fishing effort. For example, in terms of spatial effects, the longline sets in the Gulf of Mexico (82°W–96°W, 20°N–30°N) accounted for 47% of the total observed longline sets in the POP program from 1992 to 2009, but only three seabirds (2% of the total observed seabirds) were captured there. By contrast, the observed longline effort along the northeast US coast accounted for only 6% of the total observed longline sets in the POP program, but 41 seabirds (31% of the total observed seabirds) were caught in this area. Longline sets were evenly distributed among the seasons, but our modeling results suggested a higher probability of catching seabirds in the winter. These captured seabird species migrate between their breeding grounds and wintering grounds. The wintering range for most of these species (e.g., Black Backed Gulls, *Larus marinus* Linnaeus, 1758, Herring Gulls, *Larus argentatus* Pontoppidan, 1763, and Northern Gannets, *M. bassanus*) includes areas of the western North Atlantic near the northeast coast of the US (Harrison 1983, Stevenson and Anderson 1994). Therefore, migration of seabirds to wintering grounds likely increased their chances of being caught during winter in areas along the northeast US coast.

Previous studies suggested a higher probability of catching seabirds during daytime (Klaer and Polacheck 1998, Brothers et al. 1999b, Belda and Sanchez 2001). However, we did not detect a significant effect of set time on seabird bycatch. Possible reasons may include that: (1) few seabird captures limited the detectability of the effects of set time; (2) sunrise and sunset times vary with location, season, and even year; therefore, the results of set time may be subject to the definitions of day/night

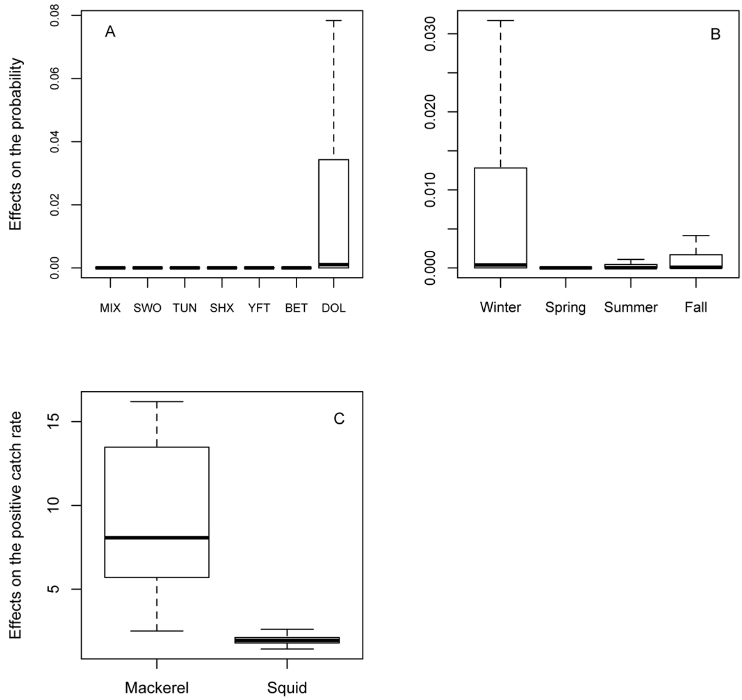

Figure 3. Effects of (A) target species and (B) season on the probability of catching seabirds and (C) effects of bait type on positive catch rate (number per 1000 hooks). MIX = mixed species, SWO = swordfish (*Xiphias gladius*), TUN = tuna (Scrombidae), SHX = shark (Selachimorpha), YFT = yellowfin tuna (*Thunnus albacares*), BET = bigeye tuna (*Thunnus obesus*), DOL = dolphinfish (*Coryphaena hippurus*). Refer to the Figure 2 legend for explanations of the box plots.

sets (although we defined day/night sets according to seasonal changes in sunrise/sunset times, our designated night times may still include some period of natural light around sunrise or sunset); and (3) the effects of set time may have been included in other factors such as season or target species (e.g., all swordfish-oriented sets are night sets).

Bait has been suggested to play an important role in seabird bycatch (Klaer and Polacheck 1998, Brothers et al. 1999b, Watson et al. 2005, Foster et al. 2012). We found a significant bait effect on seabird bycatch: on sets catching seabirds, more seabirds were caught using mackerel than using squid, which corresponds to the distribution of longline sets with mackerel (83%) and squid (16%) bait in the POP data examined. Foster et al. (2012) found that use of mackerel bait vs squid reduced the bycatch of both loggerhead [*Caretta caretta* (Linnaeus, 1758)] and leatherback [*Dermochelys coriacea* (Vandelli, 1761)] sea turtles in this fishery. They also found that the combined use of 18/0 circle hooks with mackerel bait was even more effective for reducing loggerhead sea turtle bycatch and significantly increased swordfish catch by weight. Increased use of mackerel bait in this fishery could potentially counteract or at least obscure any reduction in seabird bycatch attributable to a change from 8/0 and 9/0 J-hooks to 16/0 and 18/0 circle hooks.

The effects of target species on seabird bycatch have rarely been reported. Our results suggested a higher probability of catching seabirds when targeting dolphinfish.

Table 4. Model development for estimating the probability of catching seabirds and the positive catch rate through the stepwise selection approach. NULL = intercept of the model, YEAR = year, TAR = target species, LON = longitude (°W), HOOK = hook treatment, SEA = season, BAIT = bait type.

Variables added	df	Residual deviance	AIC	*P*-value	Change in deviance	Cumulative % of total deviance
Probability						
NULL		292.5	290.5			
YEAR	16	229.9	263.9	4.18×10^{-7}	62.6	21.4
TAR	6	205.2	251.2	3.83×10^{-4}	24.7	29.8
LON	1	189.7	237.7	8.19×10^{-5}	15.5	35.2
HOOK	3	174.6	228.6	0.002	15.1	40.3
SEA	3	160.6	220.6	0.003	14.0	45.1
Positive catch rate						
NULL		19.5	76.2			
BAIT	1	14.0	68.4	0.002	5.4	27.8

Relatively short droplines and gangions are used on sets targeting dolphinfish, resulting in a shallower position of the hooks (SEFSC 2009), which likely increases the accessibility of baited hooks to seabirds. The maximum hook depth of dolphinfish-oriented sets averaged 20 m, approximately 12 m shallower than the hooks targeting other species. Northern Gannets can dive as deep as 19.7 m (Brierley and Fernandes 2001). Model results regarding target species should be carefully considered in light of the few dolphinfish-oriented sets in the data set; only 20 (1.2%) of the 1648 analyzed longline sets targeted dolphinfish, and only three of these sets caught seabirds (total of three seabirds, one on each set).

The model for estimating the probability of catching seabirds identified year as a significant factor. Of the longline sets observed prior to 2005, only 7% used circle hooks; therefore, the low percentage of circle hooks in the data prior to August 2004 combined with its exclusive use after August 2004 may have contributed to the significance of year as an explanatory variable. Because there was little overlap in the use of hook types before and after August 2004, any other influencing factors that distinguish these two time periods (e.g., a lower population size of some affected seabird species in the latter time period) might have confounded analyses of hook effect and year effect.

This analysis focused on the hook effects on seabird bycatch, regardless of species. The probability of catching a seabird and the positive catch rate of seabirds are likely species-specific due to the different foraging behaviors. Examining the species-specific effects requires species identification, which was not well recorded in the POP data prior to 2004. Only 60% of the captured seabirds in the POP data set were identified, and 30% of these were not identified to genus. Seabird identification in the POP program has become more precise since 2004, when a seabird identification training program was initiated as part of the National Marine Fisheries Service National Seabird Program.

Seabird bycatch analyses are complicated by many factors, most of which are poorly understood (Brothers et al. 1999a). The limited number of seabird captures in the data set may cause issues in the statistical analyses that we commonly use. Given multiple potentially influencing factors and the limited number of seabird captures, the effectiveness of mitigation measures can be difficult to assess (Furness 2003).

To reduce these problems, we focused on the three areas where the proportion of positive sets was almost three times higher (2.1%) than in the overall US Atlantic pelagic longline fishing area (0.6%). Furthermore, we examined the hook treatment effect on the probability of catching seabirds and the positive catch rate in separate models, as in the delta model, to handle the data having a high percentage of zero observations. To isolate the effects of factors of interest, we applied the catch rate standardization approach used in fish stock assessments to remove confounding effects caused by multiple extraneous influencing factors (Maunder and Punt 2004). Although use of delta models and the catch rate standardization method may have relieved the problems associated with zero-inflated data and multiplicity of factors, the results of our study may still be limited by the few seabird captures in the data set. An experiment specifically designed to assess the hook treatment effect on seabird bycatch in longline fisheries might have been more appropriate than an analysis based on routinely collected observer data; however, the extremely low seabird catch in the US Atlantic pelagic longline fishery would make it difficult and expensive to conduct such an experiment.

In summary, our analyses were designed to minimize the shortcomings of the observer data and suggested that the combinations of hook type and size significantly affected seabird bycatch over the period of record. Despite low overall catch rates, expanded use of the circle hook and prohibited use of the J-hook, especially the 8/0 J-hook, should therefore reduce seabird bycatch, but recognition of its effectiveness may be masked by factors associated with bait, location, season, and fishing tactics, as well as details of hook specifications (e.g., offset).

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