Preprint, 2008
doi: 10.3354/esr00133

ENDANGERED SPECIES RESEARCH
Endang Species Res

Published online October 29, 2008

Reducing seabird bycatch in the Hawaii longline tuna fishery

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INTRODUCTION

Mortality in longline fisheries is the most critical global threat to most species of albatrosses and large petrels (Gales 1998, Brothers et al. 1999, Gilman et al. 2005). Primarily while fishing gear is being set, seabirds are hooked or entangled, dragged underwater, and drown as the gear sinks. The species of seabirds most frequently caught on longlines are albatrosses and petrels in the Southern Ocean, Arctic fulmar *Fulmarus glacialis* in North Atlantic fisheries and albatrosses, gulls, and fulmars in North Pacific fisheries (Brothers et al. 1999). Longlining occurs throughout the world's oceans, has been used since the 19th century, and is practised by small-scale domestic artisanal fisheries with small, open vessels to modern mechanized industrialized fleets from distant-water fishing nations with large vessels. Pelagic longlines, where gear is suspended from a mainline drifting freely in the pelagic environment, at depths anywhere from the sea surface to 400 m, mainly target large tunas *Thunnus* spp., swordfish *Xiphias gladius*, other billfishes *Istiophoridae* spp., dolphin fish (mahimahi) *Coryphaena* spp. and sharks. Longlines can be up to 100 km long and carry up to 3500 baited hooks (Beverly et al. 2003, Gilman et al. 2008). Incidental bycatch

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side-setting is believed to further reduce seabird access to baited hooks being set by preventing foraging seabirds from manoeuvering close to the vessel hull near where the setting operation is taking place (Gilman et al. 2007a). Adding weights to branch lines increases the baited hook sink rate, reducing the risk of seabirds being able to access baited hooks as they are being set (Brothers et al. 1999, Boggs 2001). The intent of dyeing bait dark blue, by reducing the contrast between the bait and sea color, is to make it more difficult for birds to detect the bait when foraging from above (McNamara et al. 1999, Boggs 2001, Minami & Kiyota 2002, Gilman et al. 2005, 2007a). To dye bait blue to achieve regulatory-required darkness, bait is supposed to be completely thawed and soaked in a tub with dissolved blue food coloring (Virginia Dare FD&C Blue No. 1) powder at a concentration of 4 g l^{-1} of water for 1 to 4 h (Fig. 2).

A comparative study of the efficacy of side-setting, blue-dyed bait and other seabird avoidance methods found that side-setting resulted in a significantly lower seabird catch rate than blue-dyed bait, and that side-setting provided substantial operational benefits (Gilman et al. 2007a). Other seabird avoidance methods were found to be relatively impractical for employment by crew (Gilman et al. 2007a). Although Gilman et al. (2007a) tested the comparative single factor efficacy of 3 types of seabird avoidance methods, this study used observer data to compare the efficacy of different combinations of seabird avoidance strategies employed by the fleet during conventional commercial fishing operations.

We analyzed observer data from the US National Marine Fisheries Service for the Hawaii longline tuna fishery to calculate and compare seabird bycatch rates for pre- and post-regulation periods requiring the employment of seabird avoidance methods, and different combinations of methods employed to avoid catching seabirds during the post-regulation period.

Fig. 2. Bait is completely thawed and dyed blue by soaking in a large tub with dissolved blue food coloring to achieve regulatory-required darkness

METHODS

Pre- vs. post-regulation period. To compare pre- vs. post-regulation seabird capture rates, we analyzed data from the Hawaii longline observer program for Hawaii-based longline tuna-targeting sets (defined by the US National Marine Fisheries Service [2005] as sets containing ≥15 hooks between floats) for the periods before and after seabird avoidance regulations came into effect. The analysis was conducted employing only sets where one or more albatross was observed present during setting or hauling operations and/or a seabird was captured. For sets where no albatrosses were present, the observation that no albatrosses were captured is a result of an absence of albatrosses at the fishing grounds and is not a reflection of the efficacy of any methods employed to avoid catching birds, hence the decision not to include these sets in the analysis. We only considered the presence or absence of albatross species to determine whether or not to include a set in the analysis, as captures of other seabird species are very rare events in this fishery—of 310 seabirds observed captured in this fishery from 2 March 1994 to 4 September 2007, 6 (2%) were a species other than black-footed or Laysan albatrosses. The pre-regulation period used for the purposes of the present study started on 9 May 2000, the date the observer program began recording seabird abundance during fishing operations, and ended on 9 June 2001, the day before seabird regulations went into effect. The post-regulation study period was from 10 June 2001 through 4 September 2007[2].

The number of birds hauled aboard is used to estimate the total number of seabirds captured during the set, despite evidence that this method underestimates total bird capture (Brothers 1991, Gales et al. 1998, Gilman et al. 2003, 2007a). Observers are not required to observe the entire setting of the gear, and therefore all seabird captures occurring during setting are not necessarily observed. Thus, observations of bird captures during setting operations were not used for this analysis.

It was not possible to normalize seabird bycatch rates for albatross abundance, as conducted in previ-

[2]At the time of conducting the query to the US National Marine Fisheries Service observer program database, the US National Marine Fisheries Service had not completed validating some of the observer data from longline tuna trips included in this analysis

ous experiments (Gilman et al. 2003, 2005, 2007a). This was because seabird abundance was not estimated in smoothness parameters were determined using generalized cross-validation (Wood 2006). Models were fitted using the mgcv package (Wood 2006) available for the program R (Ihaka & Gentleman 1996).

We also combined these 4 categories into 2 categories of stern- vs. side-setting, and 2 categories of 45 vs. 60 g weights employed during the post-regulation period to determine if there was a significant difference in seabird catch rates between these 2 pairs of factors. Spatial and temporal trends in seabird catch rates were estimated by fitting Poisson GAMs to the seabird catch. For the side- vs. stern-setting comparison, informative covariates included in the model were (1) time of day of set, (2) location where sets were initiated, (3) season of set, (4) whether or not bait was treated (thawed and dyed blue); and (5) size of branch line weight. For the 45 vs. 60 g comparison, informative covariates included in the model were (1) time of day of set, (2) location where sets were initiated, (3) season of set, (4) whether or not bait was treated (thawed and dyed blue); and (5) whether sets were made from the side or the stern of the vessel.

We calculated estimates of seabird catch rates for the data, based on a binomial estimator with Clopper-Pearson confidence intervals (Agresti 2002), classified by the following informative factors which could affect the bird bycatch rates: side- vs. stern-setting, 45 vs. 60 g branch line weighting, timing of the start of the set and season. We also determined the frequency of voluntary employment of different seabird bycatch reduction methods at grounds where seabird avoidance methods are not required.

There were 215 sets where an albatross was observed during the fishing operation and/or a seabird was observed captured during the haul which were excluded from this main analysis because they did not fit into one of the 4 categories (e.g. sets where a towed deterrent or tori line was deployed, sets that were made at night, sets with line weighing less than 45 g including no weight, sets with atypical line weights, and sets where a leader length was >1 m). As with the first study component, the number of birds hauled aboard was used to estimate the total number of seabirds captured during the set, and it was not possible to normalize seabird capture rates by albatross abundance.

RESULTS

Pre- vs. post-regulation period

There were 702 sets of 1 337 224 hooks during the pre-regulation period, during which 107 seabirds were observed captured. There were 3800 sets of 7 727 429 hooks during the post-regulation period, during which 166 seabirds were observed captured. Table 1 provides a summary of the data used in the Poisson regression model. The pre- and post-regulation nominal seabird bycatch rates were 0.080 (95 % CI: 0.066 to 0.097) and 0.021 (95 % CI: 0.018 to 0.025) seabirds per 1000 hooks, respectively, a significant 74 percent reduction in the pre-regulation period seabird catch rate (Table 1).

Fig. 3 presents the Poisson GAM model fit to the seabird catch rate data for the combined 4502 pre- and post-regulation period sets. The 3 covariates or factors (time of starting setting operations, season in which a set was made, and location at the start of sets) included in the model were all significant effects. Timing of initiating setting was a significantly nonlinear effect. Seabird catch rates were lowest during October to December, and seabird catch rates in all 4 quarters of the year were significantly different from each other (Fig. 3a). Seabird catch rates were lowest during sets initiated between 0:00 to ca. 05:00 h, dipped slightly around 15:00 h and then increased during early evening (Fig. 3b). Higher seabird catch rates occurred around the main Hawaiian Islands, with the highest rates in the northwestern sector at ca. 25°N, 170°W (Fig. 3c). Based on the Poisson GAM model, conditioned on the 4 covariates or factors, the seabird catch rate decreased significantly by 67 % (95 % CI: 62 to 72) from the pre- to post-regulation period (Fig. 3d). The model was a reasonable fit to the large data set and accounted for 38.2 % of the model deviance.

Of the prescribed seabird bycatch reduction methods, branch line weighting is the one gear design that was also conventionally employed during the pre-regulation period. Perhaps due to the adoption of the seabird regulation line weighting requirement, the mean amount of weight used during the post-regulation period was significantly different and higher, although only by a small amount: During the pre-regulation period, vessels conventionally employed branch line weighting with a mean of 47.4 g ± 0.4 SD, whereas the mean for the post-regulation period was 49.9 g ± 0.1 SD. When the Poisson GAM model was modified to explicitly account for this variability in branch line weighting effect on seabird bycatch rate, by including branch line weighting as a covariate, branch line weighting was found to have a significant linear effect on seabird catch rate ($p < 0.01$). We did not include branch line weighting as a covariate in the model as this is one of the seabird bycatch reduction methods included in the regulations, and we needed the GAM model to be affected by the pre- vs. post-regulation variability in the seabird bycatch reduction methods prescribed in the regulations. Unlike branch line weighting, the other seabird avoidance methods in the regulations (side-setting, dyed and thawed bait, bird curtain and management of discards) were generally only employed during the post-regulation period.

There was uneven seasonal distribution of effort, with 67, 10, 1 and 22% of sets made during the first (January to March) through 4th quarters, respectively, during the pre-regulation period, and 36, 27, 11, and 26% of sets made during the first through 4th quarters, respectively, during the post-regulation period. The Poisson GAM model explicitly accounted for the effect of seasonal distribution of effort on seabird bycatch rate. During the pre-regulation period, the seabird catch rates by quarter were 0.09 (95% CI: 0.07 to 0.11), 0.16 (95% CI: 0.10 to 0.25), 0.00 (95% CI: 0.00 to 0.43), and 0.007 (95% CI: 0.001 to 0.02) seabirds per 1000 hooks, respectively, using a binomial estimator. During the post-regulation period, the seabird catch rates by quarter were 0.03 (95% CI: 0.02 to 0.03), 0.04 (95% CI: 0.03 to 0.05), 0.005 (95% CI: 0.001 to 0.012), and 0.003 (95% CI: 0.001 to 0.007) seabirds per 1000 hooks, respectively, using a binomial estimator. The seabird capture rates were significantly higher during the first 2 quarters of the year during both the pre- and post-regulation periods. The seabird catch rates were significantly lower during the first 2 quarters of the post-regulation period relative to the first 2 quarters of the pre-regulation period, but this was not the case for the latter 2 quarters of the year.

Of the 4502 sets where an albatross was observed present during setting or hauling operations and/or a seabird was hauled to the vessel during gear retrieval, 2448 (54%) began at a location south of 23° N. Of the

Table 2. Four-dimensional contingency table providing summary statistics of seabird capture rates based on a binomial estimator

Bird bycatch reduction method	Weight within 1 m of hook (g)	Season	Time of initiating set (h)	No. of sets	No. of hooks	Seabirds captured (hauled aboard)	Seabird bycatch rate (per 1000 hooks) Point estimate	95% CI
Side-setting	45	Jan–Jun	≤7:00	25	47 108	1	0.021	0.001–0.118
			>7:00	114	244 063	10	0.041	0.020–0.075
		Jul–Dec	≤7:00	13	31 346	0	0.000	0.000–0.118
			>7:00	102	218 476	1	0.005	0.0001–0.026
	60	Jan–Jun	≤7:00	28	60 659	0	0.000	0.000–0.061
			>7:00	63	138 200	0	0.000	0.000–0.027
		Jul–Dec	≤7:00	8	19 074	0	0.000	0.000–0.193
			>7:00	15	34 996	0	0.000	0.000–0.105
			Total	368	793 922	12	0.015	0.008–0.026
Stern-setting	45	Jan–Jun	≤7:00	196	413 905	2	0.005	0.001–0.017
			>7:00	556	1 169 204	25	0.021	0.014–0.032
		Jul–Dec	≤7:00	51	110 073	0	0.000	0.000–0.034
			>7:00	420	905 543	6	0.007	0.002–0.014
	60	Jan–Jun	≤7:00	45	86 891	0	0.000	0.000–0.042
			>7:00	215	440 904	7	0.016	0.006–0.033
		Jul–Dec	≤7:00	24	48 602	0	0.000	0.000–0.076
			>7:00	126	267 512	0	0.000	0.000–0.014
			Total	1633	3 442 634	40	0.012	0.008–0.016

sector ca. 25° N, 170° W (Fig. 4c). Sets employing blue-dyed and thawed bait had a seabird catch rate 22% (95% CI: 15 to 31) lower than sets using untreated bait; the difference was statistically significant (Fig. 4e). The model was a reasonable fit to the large data set, accounting for ca. 45.4% of the model deviance.

Based on a Poisson GAM model fit to 2 categories of sets made during the post-regulation period of those made from the side vs. the stern of the vessel, conditioned on the factors of time of starting setting, season, location at the start of sets, branch line weighting, and whether or not bait was thawed and dyed blue, there was no significant difference in seabird bycatch rates between side- vs. stern-setting at the 95% confidence level ($p = 0.14$), but there was a significant difference at the 85% level ($p < 0.15$). Side-setting resulted in seabird catch rate 21% (95% CI: –8 to 42) lower than stern-setting.

There was a significant difference in seabird catch rates between sets made during the post-regulation period with 45 g weights located within 1 m of the hook and sets with 60 g weights within 1 m of the hook, when employing a Poisson GAM model fit to sets employing 45 vs. 60 g weights, conditioned on the factors of time of starting setting, season, geo-location of the start of sets, side- vs. stern-setting, and whether or not bait was thawed and dyed blue ($p < 0.01$). Sets with 60 g weights resulted in a seabird catch rate 63% (95% CI: 45 to 88) lower than sets with 45 g weights.

Of the 2001 sets in this study component, 883 sets (44% of the sample) were initiated south of 23° N where either an albatross was observed to be present during setting or hauling and/or a seabird was captured. One or more of the seabird avoidance methods were employed during these 883 sets. Side-setting was employed in 131 sets, blue-dyed bait was used in 44 sets, and weights of 45 g or more were used in 855 of the sets (no branch line weights were used in 28 sets). In the 869 sets employing weights, weights were attached to branch lines within 1 m of the hook in all but 6 of the sets, in 55 sets offal was discarded on the side of the vessel opposite to that where the sets were made, a tori (bird scaring) line was deployed during 13 sets, a towed buoy was deployed during 9 sets, and 1 set was made at night.

DISCUSSION

Seabird bycatch rates

A Poisson GAM, conditioned on time of day of setting, season and location of setting predicted that the seabird capture rate declined significantly by 67% following the introduction of seabird regulations. By explicitly accounting for these covariates and factors, this modeling approach provided a strong inference of the effect of regulatory measures involving changes in fish-

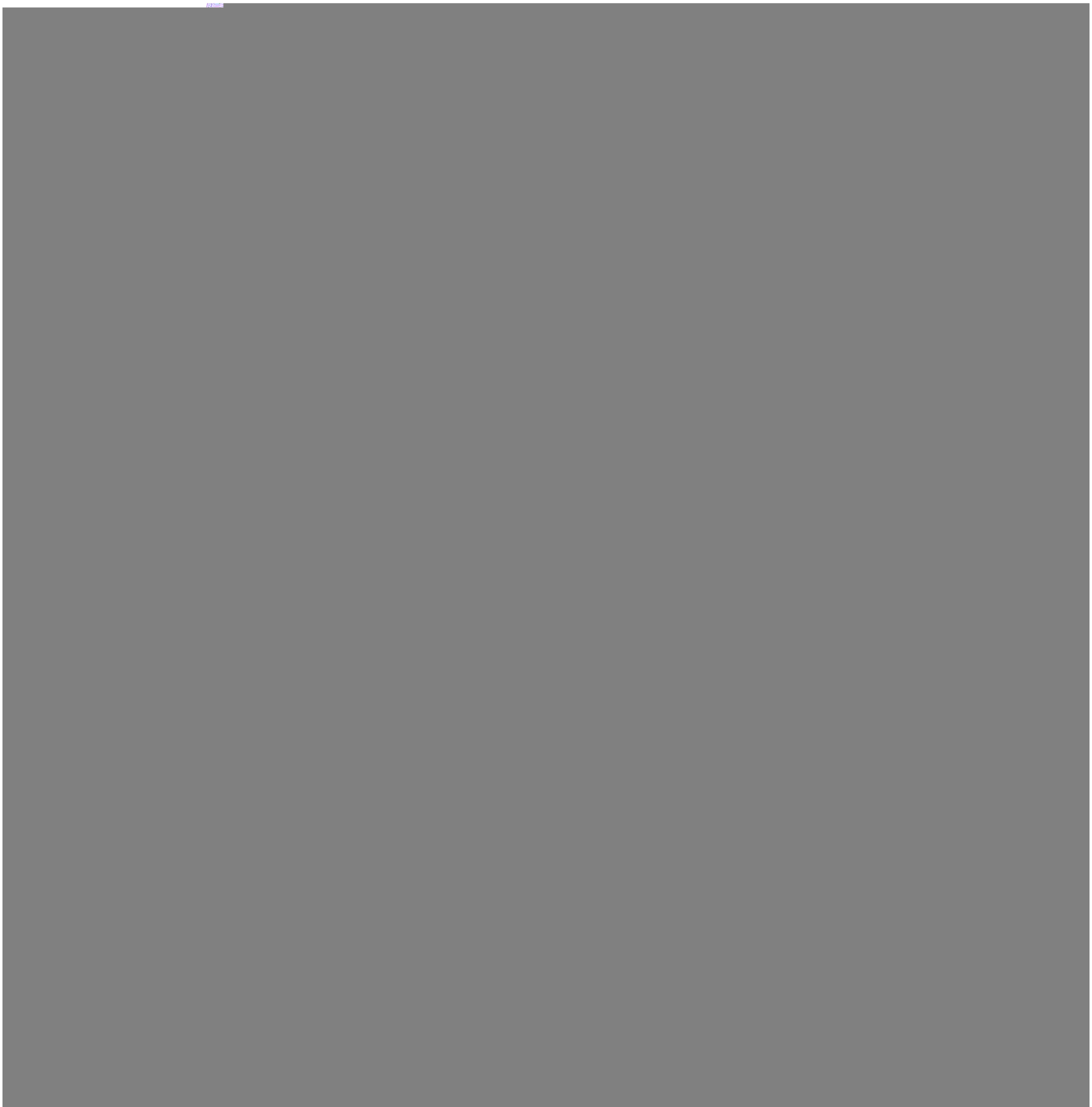

Fig. 4. Nonparametric Poisson regression model fitted to the seabird catch in sets made by the Hawaii longline tuna fishery during the period prior to seabird avoidance regulations coming into effect (n = 702 sets) and for 4 categories of seabird bycatch avoidance methods (see 'Methods; Alternative combinations of seabird avoidance methods') employed by the Hawaii longline tuna fishery during the post-regulations period (n = 254, 114, 1223, and 410 sets in the order displayed), for sets with seabird captures observed during gear hauling and/or albatrosses present during setting or hauling. (a) Seabird catch rate as a seasonal effect conditioned on the other 4 factors time of initiating setting, location of initiating sets, 5 categories of sets, and bait treatment (untreated vs. dyed blue and thawed). (b) Set time effect in the model. (c) Two-dimensional spatial (setting location) effect on catch rate; the US Exclusive Economic Zone seaward boundary is shown. (d) Effect of the 5 categories of sets conditioned on the other covariates. Pre = pre-regulations period; Po1 = side-setting with 45 g weights located within 1 m of the hook; Po2 = side-setting with 60 g weights located within 1 m of the hook (note, the *y*-value of –132.9 puts this category off the scale of the figure); Po3 = stern-setting with 45 g weights located within 1 m of the hook; Po4 = stern-setting with 60 g weights located within 1 m of the hook. (e) Bait treatment effect in the model: N = no (untreated), Y = yes (dyed blue and thawed). In (b) solid curves = model fit, dashed curves = 95% pointwise confidence bands. In (a,d,e) solid bars = mean, dashed bars = 95% confidence interval, *y*-axis = centered response scale. Reference levels are centered at zero and are as follows: (a) the first quarter of the year (January to March), (d) the pre-regulation period, (e) no bait treatment

However, because observers need to observe each haulback in full in order to record the number of seabirds captured, interactions with other protected species (sea turtles and marine mammals), handle and release any protected species brought to the vessel alive during the haul, and record other fundamental information, an additional requirement for an observer to also watch entire setting operations would leave insufficient time to sleep and eat. However, it may be feasible for observers to record albatross abundance during the first and last hour of each set, which would better characterize seabird abundance during setting than the current method.

Fishing grounds where seabird bycatch is problematic

A large proportion of albatross interactions with the Hawaii longline tuna fishery occurred south of 23° N, the southern boundary ofthe area for required employment of prescribed seabird avoidance methods by Hawaii longline tuna vessels. Management authorities originally selected this boundary to reduce the risk of interactions with the short-tailed albatross *Phoebastri albatrus* (US Fish and Wildlife Service 2002, 2004, US National Marine Fisheries Service 2005). However, the stated purpose of current regulations is to reduce interactions with all seabird species, not just the listed endangered short-tailed albatross (US Western Pacific Fishery Management Council 2004, US National Marine Fisheries Service 2005). Based on observations of where the fleet catches seabirds, to more effectively minimize seabird bycatch rates in the Hawaii longline tuna fishery, fishery management authorities should consider moving the boundary for the prescribed use of seabird avoidance measures farther south.

Voluntary use of seabird avoidance strategies

Of the seabird avoidance methods voluntarily employed by the Hawaii longline tuna vessels when fishing at grounds where seabird avoidance methods

iries -222i5ceeh7.7(,s5u 3.a,3et 5sr)tg the a3fhohen common measure (after branch line weighting) voluntarily employed by vessels on fishing grounds where seabird avoidance methods were not required. This suggests that compliance with required employment of side-setting is likely to be higher than other seabird bycatch reduction methods.

Efforts by the Hawaii longline fleet alone to reduce seabird bycatch will not reverse North Pacific albatross population decline. The Hawaii longline fleet is a very small component of the total longline fishing effort in the North Pacific, representing less than 3% of total longline hooks deployed in the Pacific Ocean each year (Majkowski 2007). Of the 61 species of seabird affected by longline fisheries, 26 are threatened with extinction, including 19 species of albatrosses, among them the Laysan and black-footed albatrosses, and there is compelling evidence that longline mortality is a significant component in the decline of many of these species (Gales et al. 1998, Brothers et al. 1999, Lewison & Crowder 2003, Niel & Lebreton 2005).

The seabird avoidance methods found to be effective in the Hawaii fishery may likewise be effective in other longline fisheries. However, different seabird avoidance methods may be appropriate for different longline fisheries due to differences in the diving abilities of seabird species that interact with each fishery, vessel designs, and fishing gear and methods (Brothers et al. 1999, Gilman et al. 2005). In particular, the very rare occurrence of interactions with deep-diving species of seabirds in the Hawaii fishery, and use of relatively large weights proximate to the hook, are important differences that need to be taken into account when considering the applicability of results from this study to other fleets. Trials in individual fisheries must precede advocacy for the introduction of specific seabird avoidance methods.

Despite the availability of effective avoidance methods that also increase fishing efficiency, most longline fleets do not employ effective seabird avoidance methods (Brothers et al. 1999, Gilman et al. 2005). Some Regional Fisheries Management Organizations (RFMOs) have recently made progress: 5 have adopted legally binding conservation measures related to reducing seabird bycatch in pelagic and demersal longline and trawl fisheries (Gilman et al. 2007b). However, these RFMO seabird conservation measures need to be improved. For instance, the areas where some of these measures are required do not include higher latitude fishing grounds, where seabird interactions have been observed to be problematic. The measure adopted by the Western and Central Pacific Fisheries Commission does not require vessels <24 m in length to employ seabird avoidance measures in areas north of 23° N; however, the present and previous studies have documented high seabird bycatch rates by vessels in this size category in this area. Furthermore, compliance by many member states with these RFMO seabird conservation measures is likely low, as observer programs and national management frameworks are generally weak or nonexistent, preventing

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