# Title: Integrated Weight Longlines with Paired Streamer Lines – Best Practice to Prevent Seabird Bycatch in Demersal Longline Fisheries

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# Integrated Weight Longlines with Paired Streamer Lines – Best Practice to Prevent Seabird Bycatch in Demersal Longline Fisheries

## Abstract

To evaluate a new technology – integrated weight longlines (IW) – as a viable seabird mitigation technology for demersal longline fisheries, we compared three experimental mitigation treatments, IW line alone, IW with paired streamer lines (IWPS) and unweighted longlines (UW) with PS (UWPS), to a control of no deterrent (UW alone). Trials took place on two vessels targeting Pacific cod (*Gadus macrocephalus*) over a five-month period in the Bering Sea, Alaska, USA. We used multiple criteria for evaluations – catch rates of all taxa, seabird abundance and attack rate, and gear sink rate and performance – making this study the largest and most comprehensive experiment of its kind.

All mitigation technologies dramatically decreased seabird bycatch rates while having little to no effect on fish catch rates. Mitigation was more effective for surface foraging seabirds (*Fulmarus glacialis* and *Larus* spp.) than for diving seabirds (short-tailed shearwaters, *Puffinus tenuirostris*), reducing mortality rates by 91% to 100% and 80% to 97%, respectively. IWPS performed best, reducing surface forager catch by 100% and shearwater catch by 97%, relative to the control. IW alone and UWPS performed similarly reducing surface forager catch by 91% and 98%, respectively, and shearwaters catch by 87% and 80%, respectively. Seabird abundance and attack rate were poor proxies of seabird mortality, especially for IW gear. IW lines reduced the distance astern that birds have access to sinking baits by near half and its handling qualities were superior to UW. We conclude that IW longlines deployed with paired streamer lines comprise the core of best management practices for seabird conservation in demersal longline fisheries using autoline systems.

**Keywords:** Seabird-fishery interaction; bycatch reduction; integrated weight longline; sink rate; cooperative research; mitigation

## 1. Introduction

The incidental catch of seabirds in fisheries is an international marine conservation problem. Although estimates of worldwide catch are lacking, hundreds of thousands of seabirds are probably caught by both pelagic and demersal longline gear annually (Nel and Taylor 2003). In the Alaska demersal groundfish longline fisheries, annual seabird mortality has averaged 15 888 birds from 1993 to 2001 although the catch has been reduced by near 70% since 2002 (2002-2005; 5 276/year; NMFS 2006). This decline is primarily due to revised mitigation regulations, which were initially focused on preventing mortalities of the endangered short-tailed albatross (*Phoebastria albatrus*), but later intended to reduce the catch of all seabirds.

Seabird catch rates in longline fisheries vary widely among gear types, seabird species present, temporal, spatial and physical factors and mitigation devices (Brothers et al. 1999; Melvin et al. 2001; Weimerskirch et al. 2000). Mitigation devices tested in demersal fisheries to date have had conflicting results for seabird catch (line shooter), were unsafe and had lower fish catch rates (manually adding weight), were not feasible in extreme weather (streamer lines) or were cost prohibitive (lining tube; Melvin et al. 2001, Lokkeborg 2003, Robertson et al. 2006). For the widest acceptance and compliance among fishers, mitigation devices should be easily assimilated into their normal fishing routine and be inviolable (Robertson et al. 2006).

Line weighting and streamer lines are integral to the seabird conservation measures of the Antarctic demersal longline fisheries managed by the Convention for the Conservation of

Antarctic Marine Living Resources (CCAMLR 2006), which, as the first regional fishery management organization to implement seabird mitigation requirements for longline fisheries, have been highly successful at reducing seabird bycatch. Furthermore, these conservation measures are considered the model for world fisheries. Line weighting minimizes the time and distance astern that birds have access to sinking hooks when setting gear. CCAMLR conservation measures specify a minimum longline sink rate and recommend, but do not require, a specific weighting regime for attached weight as well as integrated weight. Although adding and removing weights to and from demersal longlines has proven effective at sinking gear more quickly and reducing seabird mortality in Alaska longline fisheries, this process slows production, increases crew workload and can be unsafe (Melvin et al. 2001). Adding heavier weight at long intervals also creates loft in the line sinking some parts of the gear faster but not others (Robertson 2000).

Recognizing the benefits of faster sinking longlines and the limitations of attaching weight, we began developing methods to incorporate weight into the longline itself. This began in 1999 with our work in the Alaska sablefish fishery where we replaced every 10th hook (~ 11 m) with a 230 g weight (Melvin et al. 2001), and culminated in 2000 during experiments comparing the sink rates of lines with varied loadings of lead to mimic integrated weight longlines (Supplemental data). Longlines manufactured with lead integrated into the line itself (integrated weight longlines or IW) sink more quickly and more uniformly out of the foraging range of most seabirds, and therefore incorporate seabird mitigation into the fishing operations with no additional effort (Robertson et al. 2003). Based on our initial tests, collaboration with researchers in the southern hemisphere, and the increasing demand for seabird-safe fishing practices, samples of IW longlines were first manufactured by A.S. Fiskevegn beginning in 2002. Tests four weight regimes (25, 50, 75 and 100 g/m) of this new product soon followed (Supplemental data; Robertson et al. 2002). For IW to be an acceptable alternative to traditional unweighted longlines (UW) they must reduce seabird bycatch rates while maintaining fish catch rates and operational performance. Longline performance features include safety, wear, breaking strength and handling properties. Performance is especially important because the cost of IW is 15-23% higher than that of UW line.

Melvin et al. (2001) demonstrated that paired streamer lines (PS) virtually eliminated the bycatch of surface foraging seabirds such as albatrosses, fulmars (*Fulmaris glacialis* ) and gulls (*Larus* spp.) in Alaskan waters, but results showed little effect on the bycatch rate of short-tailed shearwaters (*Puffinus tenuirostris*; Figure 19C in Melvin et al. 2001), a diving seabird. Based on those findings and strong industry support, PS have become the required seabird mitigation standard in Alaskan longline fisheries. To determine if we could improve upon the performance of paired streamer lines or develop an alternative, we fished UW and IW longline with and without paired streamer lines (PS) in seabird mitigation trials targeting Pacific cod (*Gadus macrocephalus*) over a five month period in the Bering Sea, Alaska, USA. Our goal was to minimize seabird catch rates without negatively impacting target fish catch rates or increasing the bycatch rate of other taxa. In this study we evaluated three mitigation scenarios using multiple criteria. We monitored: 1) the catch rates of target and non-target species including seabirds; 2) seabird abundance and attack rate; and 3) the sink rates of both gear types to determine the distance astern at which surface foraging seabirds can access baited hooks (the seabird access window). We also evaluated the operational characteristics of IW and UW lines by quantifying the relative breaking strength and frequency of tangles, as well as documenting other qualitative measures.

## 2. Methods

### *2.1 Vessels and Gear*

Research was conducted aboard two commercial fishing vessels. Each vessel made four trips between July 15 and December 11, 2005. All longlines (groundline, mainline or hookline) were manufactured by A.S. Fiskevegn of Norway from a common lot and consisted of 9.5 mm, 4-strand Silverline - a mix of polyester and Danline (blend of polypropylene and polyethylene). Gangions (snoods) were attached to cylindrical swivels fixed with two metal crimps (eyes or stops) every 1.1 meters. IW gear was manufactured with beads of lead integrated into two of four strands yielding a load of 50 grams of lead per meter of line (50 g/m). This loading value proved optimal during preliminary testing (Supplemental data). Vessels used 13/0 Easy Baiter Fiskevegn modified J-hooks on 32-cm blue-dyed gangions deployed using either the Mustad Auto- or Super-baiter. Both vessels employed twin propellers and deployed gear near the midpoint of the stern and approximately 2.5 m above sea level. Each streamer line, also called a bird or tori line, consisted of 90-m of 5/16 in blue steel poly line. The aloft section (~60m) included double-strand streamers made of UV-protected, brightly colored tubing (Kraton®) spaced every 5 meters (Melvin et al. 2001). Each vessel was equipped with equal amounts of IW and UW longlines and each gear type was deployed a similar number of times (IW=319; UW=332) on primarily soft bottom, typical of the Bering Sea continental shelf. Characteristic of the fleet, both vessels discharged offal intermittently during all aspects of fishing operations.

### *2.2 Mitigation Treatments*

Three experimental mitigation treatments, IW line alone, IW with PS (IWPS) and UW with PS (UWPS), were compared to a control of no deterrent (UW with no streamer lines). An experimental fishing permit allowed fishing with no seabird deterrent. Three of the four treatments were deployed daily, alternating UW and IW with and without streamer lines resulting in randomization within and across days. All sets were exclusively UW or IW gear. A limit of three sets per day was used to mimic normal fishing practices by these vessels. Streamer lines were maintained at an aerial extent of 60 m and on either side of the sinking longlines in conformance with current regulations (NMFS 2004).

### *2.3 Data Collection*

Data were collected by specially trained fisheries observers or North Pacific Groundfish Observer Program (NPGOP), NOAA Fisheries Fishery Monitoring and Analysis Division, staff. For the first two trips, two observers collected data 24 hours per day sampling 50% or more of each gear retrieval (100% of hauls) for species composition. For the last two trips, a single observer was on board; hauls were randomly selected for species composition according to NPGOP protocols (NMFS 2005) yielding a sample rate of 35% - 50% of the hooks on 85% of the hauls. Vessel crew retained all seabirds caught (or notified the observer if one fell off); therefore, we assume a complete census of hooks for seabird catch. If a retention bias occurred due to presence or absence of the observer, the bias occurred across all treatments. In addition, catch rates using observer subsamples and full census were not significantly different (t-test, $p<0.05$). Operational and environmental variables were also recorded for each set.

Seabird abundance and attack rate data were collected during each daylight and more than half of the dawn and dusk gear deployments (weather permitting). Seabird abundance within a 100-m hemisphere astern was estimated prior to each attack rate sample. Attacks, or bait attempts within 1-m of the longline, were estimated by seabird species and distance astern (10-m increments) during one or two 15-minute observation periods per set. Distance estimates were made using a measuring line or streamer lines for reference. Abundance and attack rate protocols are described more fully in Melvin et al. (2001).

Seabird carcasses were collected and necropsies performed by U.S. Geological Survey staff using standard protocols. Breeding status was assessed based on the presence of the bursa of Fabricius (Broughton 1994).

### *2.4 Analyses - Catch*

Generalized additive models (GAMs; Hastie and Tibshirani 1990, Venables and Ripley 1994) were used to evaluate factors influencing catch rates including treatment effects (treatment models). All variables in Table 1 were included in initial models. Abundance and attack rate data were excluded from treatment models because data were not collected during no or low light conditions typical of night time (i.e., sample size reduced by more than 45%). A loess smoothed function was considered for all continuous variables. Since

GAMs cannot accommodate explicit interaction terms, a loess smoother was used to address only the continuous variables that were most likely to have interactions (i.e., latitude and longitude, wind speed and swell). We modeled catch rates of surface foraging seabirds (northern fulmars and gull species) and diving seabirds (shearwater species) separately due to behavioral differences. In addition, the sets included in the shearwater models were limited to the time period that these seasonal migrants were consistently observed in the system (i.e., July 15 - September 29, 2005). Models were fitted using S-Plus 2000 (Insightful Corp., Seattle, WA, USA) and were specified with an error distribution appropriate to the data. A binomial error distribution was used for shearwater models due to extremely low catch levels (Table 2). Since the catch of surface foragers was overdispersed, a quasi-likelihood estimate of the error distribution was used for the surface forager models that included a log link and variance equal to the mean. Catch rates of fish (cod, halibut (*Hippoglossus stenolepis*) and other bycatch) were modeled as a log-transformed response and with a Gaussian error distribution. Other bycatch consisted of all other fish and invertebrates caught; Rajidae, Pleuronectidae, Gadidae, Cottidae and Sebastidae were the predominate families. Variables were selected using an approximate F-test ($p<0.05$) in a forward and backward stepping process (Chambers and Hastie 1992). Post-hoc tests were performed using Bonferroni techniques.

We also investigated the effects of abundance in the wake zone (out to 100 m) and attack rate on seabird catch rates using the same variables (hereafter referred to as behavior models). Sample sizes were reduced by 46% and 45% for surface forager and shearwater models, respectively, when these behavioral variables were included.

### *2.5 Analyses – Abundance and Attack Rate*

We used generalized linear models with Bonferroni post-hoc contrasts to evaluate differences in seabird abundances and attack rates among treatments. Since performance standards in Alaska require streamer lines to have an aerial extent of 60 meters, we also used the percent of attacks within 60 meters astern as a response variable to compare attack rates among mitigation treatments and the control. Analysis of variance (ANOVA) was used to compare the differences in the percent of attacks within 60-m astern among gear types with and without streamer lines for the three most abundant species. Multiple comparisons were performed using Tukey's honestly significant difference (HSD) test. As in the catch models, the analyses for shearwaters were limited to the July 15-September 29 time period.

### *2.6 Sink Rate and the 2-m Access Window*

Preliminary testing of the integrated weight concept was performed in 2000 and 2002 on multiple vessels. Supplemental data and Robertson et al. (2002) provide more detail on the development of IW gear tested in this experiment. The sink rate of UW and IW gear was measured with Mk9 time-depth recorders (TDRs; Wildlife Computers, USA), which recorded depth at 0.5 m increments every second. TDRs were acclimated to surface sea water temperatures for up to 30 minutes prior to gear deployment to minimize anomalous measurements following protocols described by Robertson et al. (2006). Seven to ten TDRs were deployed approximately every 1 100 hooks (or one magazine) and 1 km or more from anchors on each of 29 UW and 28 IW sets.

Differences in time for each of the two gear types to reach a depth of 2-meters was evaluated using a linear mixed effects model (LMEs; Pinheiro and Bates 2000). This depth benchmark was selected because surface foragers in this system (fulmars, gulls and albatrosses) make up the majority of bycatch and cannot access longlines beyond 2-m in depth (Whittow 1993a, b, Hatch and Nettleship 1998, Gilchrist 2001). The response variable (seconds) was log-transformed to minimize skewness. Since multiple TDRs were deployed per set, set was specified as a random effect. In addition to gear type, environmental variables and vessel effects were included in the LME. In order to make comparisons between vessels that are more relevant to seabirds, we also calculate the 2-m seabird access window, distance astern (m) that the gear is within 2-m of the surface, by multiplying the time to 2-m depth by vessel setting speed (m/s).

### *2.7 Operational Characteristics*

In order to evaluate potential operational issues, we compared the breaking strength of new and used longlines using an Instron 5585H static load frame (250kN capacity) connected to Bluehill 2 materials testing software and a pull rate of 500 mm/min. Used gear tested was either fished for 5 months (the duration of this experiment) or ~1.5 years (prior to retirement). We pooled data from both vessels for each gear type and age and ANOVA was used to evaluate effects of these on breaking strength (kN). We also monitored the frequency of tangles, conservatively defined as three or more hooks fouled together, during line hauling observations.

## 3. Results

We deployed more than 13 million hooks in 650 sets (average 20 000 hooks/set). Ninety-four percent of sets were sampled and 48% of all hooks retrieved were monitored for species composition. A total of 443 birds were caught in the course of this research program. Sets conforming to experimental protocols and used in analyses included 394 seabirds (Table 2). Most were fulmars and gulls caught in the control of no mitigation (UW; Table 2). Mortality events occurred on 33% of UW sets, 9% of which had more than one bird. The highest mortality event was 60 birds.

Of the birds examined for hooking location (nearly half), 49% were beak hooked, 37% in the wing and the remaining were hooked in the head, neck or body. Necropsies were performed on 417 birds. The male to female sex ratios by species were: fulmars 28:71; gulls 55:43 and short-tailed shearwaters 44:56 (Hatch et al. In prep.). Ten percent of fulmars, 19% of gulls and 71% of the shearwaters were pre-breeders.

### *3.1 Treatment Effects - Catch*

Significant factors in seabird catch rate treatment models differed by foraging guild (Table 3). The final treatment model for surface foraging seabirds explained 67% of deviance. Mitigation treatment explained the most deviance (28%) relative to other variables. Depth, deployment location (loess smoothed function of latitude and longitude), time-of-day, distance from last retrieval, cloud cover and the smoothed function of swell height and wind speed were also significant (Table 3). In general, as fishing depth increased, surface forager catch rates decreased; as swell and wind increased, catch rates increased; and as distance from the last retrieval increased to ~10 nmi, catch rate increased, then decreased between 10-25 nmi and increased again beyond 25 nmi.

The final treatment model for shearwater catch rate explained 74% of deviance. Like the surface forager model, mitigation treatment explained the most deviance (14%) relative to other variables. Significant variables were similar to the surface forager model except for depth, cloud cover, distance from last retrieval and moon phase (Table 3). Swell height and sea state were significant for shearwaters. In general catch rates were higher during the new moon and during the crepuscular periods (dawn and dusk) and as swell and sea state increased, catch rates decreased for this migratory species.

Catch rates of surface foraging and diving seabirds were dramatically reduced by all mitigation methods (80% to 100%) compared to controls, but their relative effectiveness varied by foraging guild (Figure 1). IWPS yielded the lowest bycatch rates of all mitigation treatments reducing surface forager catch by 100% and shearwater catch by 97%, relative to the control; however, the difference among mitigation treatments was significant for shearwaters only. IW alone and UWPS performed similarly, reducing surface forager catch by 91% and 98%, respectively, and shearwater catch by 87% and 80%, respectively. Differences between IW and UWPS were not significant for either foraging guild. In addition, seabird catch using IW and IWPS were not significantly different for shearwaters.

Variation due to temporal variables was explored further due to their potential for management applications. Catch rates of surface foraging seabirds and shearwaters varied by time-of-day (Table 3). Mean catch rate of surface foragers was highest during daytime hours and at dawn but lowest at night (Figure 2). Although mean catch rates were higher at dusk than night, the difference was not significant ($\alpha$ =0.05 in Bonferroni multiple comparison of time-of-day using final surface feeder model without mitigation). Mean shearwater catch rates were highest during the crepuscular periods and significantly different than day (Figure 2). No shearwaters were caught at night. Month was not significant in treatment models for either foraging guild, although there was considerable variation in the catch rates of gulls and fulmars (Table 3; Figure 3).

The inclusion of abundance and attack rate in the behavior models yielded slightly different results than the treatment models for both foraging guilds. The behavior model for surface foragers explained less deviance (50% of model deviance) and fewer variables were significant compared to the treatment model (i.e., only location, treatment and abundance; Table 3). The shearwater behavior model explained more of the deviance (82%) than the treatment model and significant variables varied slightly. Time-of-day was not significant in either the surface forager or shearwater behavior model and a few related physical variables either became or were no longer significant (i.e., sea state and smoothed function of swell and wind). A loess function of wake zone abundance was significant in both the surface forager and shearwater behavior models, but attack rate was not significant for either guild. In all cases, increases in abundance increased catch rate from zero to some threshold beyond which there was no effect.

Catch rates of cod and halibut did not vary across mitigation methods and controls (Figure 1); fishing location, month and hauling speed were consistently significant contributors predicting catch rate of cod and halibut (Table 4). Treatment was significant in the model for bycatch species other than halibut (other bycatch); the mean catch rate of other bycatch with IW alone was significantly less than other treatments in post-hoc tests. The cod, halibut and other species catch rate models explained 48%, 51% and 41% of model deviance, respectively, indicating that additional variables not accounted for may be affecting catch rates. Unlike seabirds there was no difference in cod, halibut or other bycatch across times-of-day (Figure 2). Cod catch rates varied by month (Table 4) and were lowest in September and October (Figure 3). Halibut and other bycatch rates also varied by month (Table 4).

### *3.2 Treatment Effects – Abundance and Attack Rate*

Both streamer line mitigation methods (UWPS and IWPS) significantly reduced the abundance and attack rates of surface foraging seabirds relative to the control and IW. Streamer line treatments also reduced shearwater abundance, but only UWPS reduced shearwater attacks (Figures 4 and 5). IW alone had no effect on the abundance or attack rate of either foraging guild – both mirrored the controls – and neither measure of behavior reflected the pattern or magnitude of catch rate reductions across mitigation methods.

The distribution of attack rates as a function of distance from the stern was similar in response to UW and IW alone for all species/guilds (Figure 5). Both streamer line treatments (UWPS and IWPS) virtually eliminated attacks of all species within 60 m – the aerial extent of streamer lines – where longlines are most vulnerable to attacks (Figure 5). However, shearwater attacks increased beyond 60 m, dramatically in the case of IWPS. Both streamer line treatments significantly reduced the percent of attacks within 60 m for fulmars, gulls and shearwaters (all $p<0.0001$) compared to UW whereas IW did not differ from UW (Figure 6).

### *3.3 Sink Rate*

Sink rates, measured as seconds to 2-meters depth, of UW longlines varied considerably among vessels during preliminary trials (Supplemental data) and in this study (Table 5) ranging from 17.7 to 34.1 seconds. In this study, gear type (UW vs. IW), vessel and average wind speed were significant predictors of time to 2-meters in depth (F-tests: gear type, $p<0.0001$; vessel, $p<0.0001$; wind speed, $p=0.0016$). Swell height, wind direction and sea state were not significant. Both IW and UW gear sank 1.6 times faster from Vessel A (Table 5), which set gear into the downdraft of the propeller wash, than from vessel B, which set gear into the updraft of the propeller wash. Despite vessel specific differences in sink rates, IW sank proportionately faster (1.9 times) than UW from both vessels yielding a 47% reduction in the distance astern (Table 5) that gear was vulnerable to surface foraging birds (to 2 m depth access window).

### *3.4 Operational Characteristics*

Mean breaking strength varied significantly by both gear type (F-test, $p=0.000$) and age (F-test, $p=0.000$) although age explained most of the variance (67%). In general, the mean breaking strength of IW gear was slightly lower than that of UW independent of age (New:

12.4 and 11.8 kN for UW/IW; Used 5-months: 10.1 and 8.8 kN; Used 1.5 years: 8.2 and 6.5 kN), but the breaking strength of used gear was considerably lower than new gear regardless of gear type (19% for UW and 25% for IW based on 5-month values).

Monitoring the frequency of line tangles during observation of the haul revealed that IW (0.20 tangles per 1000 hooks) tangled half as often as UW (0.38 tangles per 1000 hooks).

## 4. Discussion

### *4.1 General*

This study is the largest and most comprehensive study of seabird bycatch mitigation technologies to date. Over 13 million hooks were deployed over a range of seasons. Mitigation measures were evaluated relative to a control of no deterrent using independently collected data on all catch, seabird behavior while setting gear, sink rates of longlines, and operational variables. All mitigation technologies dramatically decreased seabird bycatch rates while having little to no effect on fish catch rates – target or bycatch species.

That short-tailed shearwaters were more difficult to deter was expected due to their increased ability to access baits for greater distances astern of the vessel; short-tailed shearwater diving depth has been documented up to 71 m (Weimerskirch and Cherel 1998). Fortunately, shearwater bycatch in the Bering Sea longline fisheries is relatively low (~ 5% of the total; NMFS 2006) due to minimal temporal overlap of the fishery with their post-breeding migration to the Bering Sea (May to September; Marchant and Higgens 1990).

Although a statistical difference in mean catch rate among the three mitigation treatments was found only for shearwaters when IW was used in tandem with paired streamer lines, IWPS also yielded the best results for surface foragers. IWPS completely eliminated mortality of surface foraging seabirds and reduced the bycatch rate of short-tailed shearwaters by 97%.

IW without streamer lines reduced the mortality rates of surface foragers by 91% and short-tailed shearwaters by 87% - rates similar to the performance of paired streamer lines with unweighted gear (98 % and 80% reduction in surface forager and shearwater catch rates, respectively). This dramatic decrease in mortality with IW alone was not reflected in either abundance or attack rate data. The magnitude and distribution of attacks on baits for IW gear (including the percent of attacks occurring within 60 m of the stern) were nearly identical to those when no deterrent was used. One possible explanation for this decoupling of observed behavior and mortality is that birds continue to attempt to take baits from hooks on fast sinking IW longlines and presumably these attempts are less successful. Regardless of the explanation, attack rate is a poor proxy of seabird mortality for IW gear deployed with autoline systems. This result is consistent with our work evaluating attached weights (Melvin et al. 2001).

Few studies have demonstrated a clear relationship between seabird abundance or attack rate and mortality (but see Gilman et al. 2003). Ashford et al. (1995) noted that high mortality coincided with intense feeding activity but may have more to do with complex behavioral interactions among species. Unfortunately, the raw data was lost in a vessel fire and a full statistical analysis was not performed. Weimerskirch et al. (2000) found no significant relationship between abundance and mortality for all species except black-browed albatross (*Thalassarche melanophris*) although abundance was not included as a variable in their GLM models. Finally, black-browed albatross abundance was a significant predictor of catch in several GLM models performed on South Atlantic longline data (Reid and Sullivan 2004). However, similar to our study, they also found attack rate to be significant only when the data was limited to a smaller subset and suggested that the relationship between attack rate and catch may not be linear. We also concur with Reid and Sullivan (2004) that intra- and inter- specific competition during line setting may have a stronger influence on catch than simply the number of birds or attack rate.

Despite their significance as predictors of catch rate in the behavior models, abundance and attack rate were inconsistent proxies of seabird mortality for streamer line treatments. Overall, when streamer lines were used, seabird abundance and attack rates were significantly reduced for all species relative to IW and controls with the exception of short-tailed shearwater attacks in response to IW coupled with streamer lines. However, changes in the magnitude of attack rates and the distribution of attacks differed markedly for short-tailed shearwaters with and without IW. IWPS had no effect on the magnitude of short-tailed shearwater attack rates relative to controls, while UWPS attack rates were significantly decreased. Although significantly fewer short-tailed shearwater attacks occurred within 60 m of the stern when streamer lines were used with both UW and IW (UWPS and IWPS), attacks increased beyond 60 m – the aerial extent of streamer lines – but more so for IWPS. Behavioral differences beyond those measured in this study might explain why short-tailed shearwater attacks increased sharply beyond 60 m when IW was combined with PS. In contrast, surface forager attack rates decreased significantly overall and attacks were virtually eliminated out to 100 m (relative to UW), but peaked slightly at 60 to 70 m astern in response to both streamer line treatments.

### *4.2 Temporal Effects*

Our experimental design, which incorporated a control of no deterrent, allowed us to unambiguously evaluate the performance of seabird mitigation technologies. Similar to our earlier work in Alaska demersal fisheries (Melvin et al. 2001), seabirds were caught on 33% of sets where no deterrents were used and 8% of sets when UWPS, the regulatory standard, was used. The low frequency of seabird bycatch, especially relative to number of hooks, underscores the perceptual paradox fishermen confront: seabird bycatch is rare in an environment where they are surrounded by hundreds to thousands of birds yet they are required to reduce the number and size of these low frequency events via mitigation. Although the pattern of bycatch rates varied significantly by times-of-day for surface foragers and short-tailed shearwaters, they were lowest at night for both foraging guilds. This is in sharp contrast to our earlier work in the Bering Sea that showed the highest seabird catch rates occurred at night (Melvin et al. 2001). The earlier study took place primarily in summer which may explain the discrepancy and high catch rates at night were driven by large events. Reduced seabird catch at night found in this study is consistent with other studies (Klaer and Polacheck 1998, Weimerskirch et al. 2000) and supports calls for night setting as a mitigation option for seabirds, diurnal foragers in particular (CCAMLR 2005).

The mean gull and fulmar bycatch rate peaked in October and November and was an order of magnitude higher than the shearwater peak in the summer. This finding suggests that reconfiguring the cod season to earlier in the calendar year could reduce total bycatch with little effect on fish catch rates in this fleet. For example, if management priority were given to fulmars and gulls because they are caught most often, avoiding peak bycatch of these surface foragers in late fall could reduce annual seabird bycatch by more than 40% (Dietrich et al. Submitted.). However, shifting the season could result in increased effort when post-breeding shearwaters and albatrosses are most abundant – May through October – resulting in higher shearwater and albatross catch. Balancing trade offs in risk to specific species would require an elaboration of seabird conservation goals as well as fishery management goals as they pertain to other prohibited bycatch species such as Pacific halibut.

Necropsies of birds caught in this study showed even sex ratios for gulls and short-tailed shearwaters but more than twice as many female fulmars were caught. Additionally, a large proportion of short-tailed shearwaters were immature. It is unclear whether this is due to a higher proportion of immature birds feeding at vessels or in the fishing areas or whether younger, less experienced birds were unable to avoid being hooked while feeding on baited hooks. If this study is representative of all longline catch in the Bering Sea, there is potential for a long term effect on demographics (Croxall et al. 1990); however, necropsy data on bycaught birds in Alaska from recent years were not available for comparison.

*4.3 Longline Sink Rates and the 2-m Access Window*

Sink rate data demonstrated that longlines with weight manufactured into the line reduces risk to seabirds by minimizing the distance astern that birds have access to sinking baits. In this study the 2-m access window was reduced by nearly half from 76 m and 92 m with unweighted gear to 40 m and 49 m with IW for the two vessels, respectively. This reduced 2-m access window resulted in the gear sinking out of the range of surface foraging seabirds closer to the vessels, and specifically within the 60-m aerial extent of our streamer lines.

This study and our data from 2000 and 2002, also clearly show that the sink rate of a specific longline product, and the 2-m access window associated with it, can vary dramatically by vessel. This variation in sink rate is affected by how the gear is set relative to the propeller rotation, but more importantly, by the variation in vessel setting speed (Melvin and Wainstein 2006). For example, a longline sinking at 0.2 m/s (or 10 s to reach 2 m) while setting gear at 3 m/s will yield a 2-m access window of 30 m while the same line set at 4 m/s will yield an access window of 40 m. In this study, sink rate and setting speed were offsetting between vessels yielding similar 2-m access windows. Vessel A with the fastest IW sink rate (0.23 m/s to 2 m; Table 6) set gear at 4.2 m/s (8.2 knots) resulted in a 2-m access window of 40 m, while vessel B set gear with a slower sink rate (0.15 m/s) set gear at 3.2 m/s (6.3 knots) yielded a 2-m access window of 49 m. Although the second vessel had baited hooks available to birds 9 meters farther astern, ‘vessel’ was not a significant factor in either seabird catch model. This suggests that although a difference was detectable in the access window, it did not affect bird catch rates for either seabird foraging guild encountered in this study. Had the vessel speeds been reversed – the faster vessel setting speed matched with the lower sink rate and vise versa – the resulting access window for the faster vessel would approach 64 m – near double that of the slower vessel. Yet it is important to note that both vessels would have met the CCAMLR minimum sink rate requirement of 0.2 m/s to a depth of 15 m for IW lines (CM 24-02, CCAMLR 2005; Table 6). This comparison illustrates that longline sink rate alone fails to fully capture the risk posed to seabirds by longlines and that a measure such as the 2-m access window described here or another system-specific measure, which incorporates vessel speed, would make a superior standard.

### *4.4 Practical Considerations*

Similar to Robertson et al. (2006) we found that the handling qualities of IW line were far superior to that of traditional UW. The result that IW line tangled with itself near half as often as UW, was presumably due to the enhanced memory and stiffness that added lead creates. Crew members in this study agreed that the heavier IW line moved more smoothly than UW through the autoline system during both the set and the haul. Also the leaded line maintains a loop when hung on a magazine, which minimizes tangles between adjacent loops during line setting. Fewer tangles and these superior handling qualities could lead to more efficient operations overall and possibly more fish over the course of a fishing year due to increased efficiency.

Although we determined that IW line breaks at 5% to 21% less force relative to UW gear, these differences were not detected in fishing operations. Decreased strength may occur due to the fact that IW line has less fabric to accommodate the addition of lead. If this difference were deemed problematic, the diameter of the line could be increased to achieve the desired breaking strength. The life of UW gear in Alaska is typically 1.5 to 2 fishing years before it is replaced. Both vessels employed in this study now use 50 g/m IW exclusively in both shallow and deep-water fisheries.

By virtue of the added lead, 50 g/m IW increases the suspended weight of longlines in an autoline system by 42 % compared to traditional UW. In the case of the vessels hosting this study, full conversion to IW (40,000 and 50,000 hooks, respectively) required reinforcement of the rack system to compensate for 2.2 to 2.8 tons of added weight. Concerns that the weight might increase wear on hooks, gangions, and the stainless steel racks proved unfounded. Vessels converting to IW longline should evaluate the potential consequence of added weight on the longline rack system and vessel stability.

Integrated weight longline is also available from O. Mustad & Son A.S., but utilizes a different technology. Mustad reports breaking strengths at 13.6 and 14.0 for Scanline 9.2 mm UW and IW gear, respectively, which are comparable to the breaking strengths we observed.

### *4.5 Broader Applications*

In the New Zealand ling (*Genypterus blacodes*) fishery Robertson et al. (2006) compared seabird catch rates between 50 g/m IW and UW lines both coupled with a single streamer line. Shearwater catch rate comparisons between studies – short-tailed shearwaters in our case and sooty shearwaters (*Puffinus griseus*) in the New Zealand study – are most meaningful because they are very similar diving seabirds, are among the most difficult to deter, and are common to both areas. In our study, the percent reduction in short-tailed shearwater catch with IW (97%-IWPS and 87%-IW) was much greater, and the magnitude of the bycatch rate (0.0005 and 0.001 short-tailed shearwaters/1,000 hooks for IWPS and IW alone, respectively) was considerably lower than for IW with a single streamer line in the ling fishery (61% and 0.06 sooty shearwaters/ 1,000 hooks). Why results between the two studies are so different for these congeneric shearwaters is difficult to say. The lack of agreement in percent reduction is likely an artifact of the control in the ling fishery, which included the use of a single streamer line, whereas in our study the reference standard was a true control of no deterrent. That there was over an order of magnitude difference in shearwater catch rate between studies could be due to a number of factors: differences in species and the species complexes present, the scope (New Zealand study was 37 days during the shearwater pre-incubation stage while the Alaska study was 5 months during the post-breeding stage including 2.5 months when shearwaters were absent), and/or paired streamer lines used in the Alaska study were more effective than the single streamer line used in the New Zealand study.

Addressing the latter possibility, the distributions of attacks astern of the vessel with known aerial extent of streamer lines and known 2-m access windows for both studies provide the best insight into differences. Based on the data provided in Robertson et al. (2006; setting speed of 3.1 m/s; 10 sec and 25 sec to 2 m depth for IW and UW, respectively), IW in the ling fishery achieved a 2-m access windows of 31 m compared to 40 m to 49 m in the Alaska study. In both the Alaska study and the New Zealand study, 50 g/m longlines sank beyond 2 m within the aerial extent of streamer lines (60 m and 50 to 60 m, respectively). Sooty shearwater and white-chinned petrel (*Procellaria aequinoctialis*) attack rates in the New Zealand study peaked within 60 m of the stern when a single streamer line was used, whereas in our study, paired streamer lines virtually eliminated attacks of all seabirds within 60 m where birds are most at risk. This contrast strongly suggests that two streamer lines outperformed a single streamer line by excluding seabirds, regardless of guild, from within the aerial extent of streamer lines.

In Alaska fisheries, seabird bycatch rates have been reduced by approximately 78% coincident with the use of paired streamer lines with a 60-m aerial extent in that fishery since 2002 (NMFS 2004). Paired streamer lines have been required in the Australian longline fisheries off Heard Island since 2003 and compliance has been nearly 100% (G. Robertson, pers. com.). Responding to anomalously high bycatch rates of seabirds in the French exclusive economic zone (CCAMLR Subarea 58.6 and Division 58.5.1), CCAMLR strongly recommended a minimum of two streamer lines be used in that fishery together with line weighting, preferably 50 g/m IW, beginning in 2003/2004 (SC-CAMLR-XXII, Annex 5, paragraph 6.29) and paired streamer lines were compulsory beginning in 2005

(SC-CAMLR-XXIV, Annex 5, Appendix O, paragraph 36 (ii)). However, CCAMLR stopped short of requiring paired streamer lines in all convention area fisheries until more data were available demonstrating the benefits and feasibility of their use in fisheries of the southern oceans (SC-CAMLR-XXII, Annex 5, paragraph 6.107). The data presented here and those in Melvin et al. (2001) and Melvin et al.(2004), and the fact that paired streamers are mandatory in high-risk fisheries, together strongly suggest that paired streamer lines are superior to single streamer lines in preventing seabird mortality. Coupled with 50 g/m integrated weight longlines, paired streamer lines comprise the core of best management practices for seabird conservation in demersal longline fisheries using autoline systems.

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## Tables

**Table 1** Initial variables included in catch models. * Included in behavior models only.

**Table 2** Summary of birds caught (includes fisher reported mortalities) by mitigation treatment and control (UW: control of unweighted longline; IW: integrated weight longline; UWPS: unweighted longline plus paired streamers; IWPS: integrated weight longline plus paired streamers). Sample sizes (parentheses) indicated under treatment headings.

**Table 3** Significance of variables in the final surface foraging seabird and shearwater treatment and behavior models. Total explained deviance is shown in parentheses. Sample sizes (parentheses) differ due to missing values in one or more covariates and behavior models exclude all sets without behavior observations (i.e., mostly night sets). “lo()” indicates the variable was significant when included as a loess smooth function (i.e., the relationship was not linear). Percent deviance for individual variables was calculated using the change in deviance as each variable was removed individually (not additive to total explained deviance).

**Table 4** Significance of variables in the final cod, halibut and other bycatch catch models. Total explained deviance is shown in parentheses. Sample sizes differ due to missing values in one or more covariates. “lo()” indicates the variable was significant when included as a loess smooth function (i.e., the relationship was not linear). Percent deviance was calculated using the change in deviance as each variable was removed individually (not additive to total explained deviance).

**Table 5** Time (seconds) to 2-m depth and 2-m access window (distance astern in m) by vessel and gear. Number of TDRs deployed and number of sets measured are separated with backslash under N.

**Table 6** Sink rates (m/s) to 2, 15, and 20-meters depth for 9.5mm unweighted (UW) and 50 g/m integrated weight (IW) longlines (for comparison purposes to Robertson et al. 2006). N recorded as number of TDR observations / number of sets. Vessel A set faster (8.2 knots) but deployed gear into propeller downwash; Vessel B set slower (6.3 knots) and deployed gear into upwash.

## Figures

**Figure 1** Mean catch rates (±SE) of surface foragers (gulls and fulmars; a) shearwaters (b) and fish (c) by mitigation treatment and control  (UW: control of unweighted longline; IW: integrated weight longline; UWPS: unweighted longline plus paired streamers; IWPS: integrated weight longline plus paired streamers). Letters above bars (a, b) and within bars (c) indicate significant differences in Bonferroni post-hoc comparisons (p<.05; the same letter is equivalent to not significant). Sample sizes (number of sets) for each treatment indicated below x-axis.  Scale of y-axis for surface foragers (a) is three times greater than that of shearwaters (b).

**Figure 2** Mean catch rates (±SE) of **s**urface foraging seabirds (a), shearwaters (b) and fish (c) by time-of-day without mitigation. Letters above bars indicate significant differences in Bonferroni post-hoc comparisons (p<.05; the same letter is equivalent to not significant). Sample sizes (number sets) for each time-of-day indicated below x-axis.  Scale of y-axis for surface foragers (a) is twice that of shearwaters (b).

**Figure 3** Mean catch rates (±SE) of surface foraging seabirds (a), shearwaters (b), and fish (c) by month without mitigation. Sample sizes (number sets) for each month indicated below x-axis. Scale of y-axis for surface foragers (a) is an order of magnitude greater than that of shearwaters (b).

**Figure 4** Mean abundance (±SE; a) and attack rate (b) of surface foraging seabirds and shearwaters by mitigation treatment and control (UW: control of unweighted longline; IW: integrated weight longline; UWPS: unweighted longline plus paired streamers; IWPS: integrated weight longline plus paired streamers). Letters above bars indicate significant differences in Bonferroni post-hoc comparisons (p<.05; the same letter is equivalent to not significant). Sample sizes (number sets) for each month indicated below x-axis. Abundance scale differs between surface foragers and shearwaters.

**Figure 5** Seabird attacks per minute by distance astern for fulmars (a), gulls (b) and shearwaters (c) by mitigation treatment and control. UW: control of unweighted longline; IW: integrated weight longline; UWPS: unweighted longline plus paired streamers; IWPS: integrated weight longline plus paired streamers. Sample sizes (number of sets) for fulmars (a) and gulls (b) were 151, 115, 173 and 157 and shearwaters (c) were 121, 84, 118 and 118 for UW, IW, UWPS and IWPS, respectively.

**Figure 6** Percent of seabird attacks within 60 meters astern (±SE). UW: control of unweighted longline; IW: integrated weight longline; UWPS: unweighted longline plus paired streamers; IWPS: integrated weight longline plus paired streamers. Letters indicate post-hoc differences among mitigation treatments and control within species. Sample sizes (number of sets) for fulmars (a) and gulls (b) were 117, 100, 102 and 97 and shearwaters (c) were 78, 66, 64 and 73 for UW, IW, UWPS and IWPS, respectively.

**Table 1**

| **Variable** | **Definition / Type** |
|---|---|
| Month | Month gear was deployed / categorical |
| Time-of-day | Day, dawn (civil twilight to sunrise), dusk (sunset to civil twilight), night / categorical |
| Location | Latitude and longitude / continuous |
| Vessel | Vessel name / categorical |
| Speed | Speed of gear deployment / continuous |
| Depth | Average fishing depth (m) / continuous |
| Other boats | Number of other boats within 12 nmi / continuous |
| Distance from last retrieval | Distance from last retrieval to new gear deployment (nmi)/ continuous |
| Fishing duration | Minutes hooks in water (first hook in to last hook out) / continuous |
| Hook retrieval speed | Hooks retrieved per minute / continuous |
| Barometric pressure | Barometric pressure (millibars) / continuous |
| Barometric pressure change | Rising, falling, stable (to be classified as anything but stable pressure had to change >5 mb in the previous 12-hour period) / categorical |
| Cloud cover | Percent cloud cover (0, 25, 50, 75 or 100%) / categorical |
| Visibility | 4-levels of distance / categorical |
| Wind | Average wind speed / continuous |
| Wind direction | Wind direction relative to setting direction (cross, parallel, variable) / categorical |
| Swell | Swell height (m) / continuous |
| Sea state | Beaufort sea state / categorical |
| Moon phase | New or full / categorical |
| Treatment | UW, IW, UWPS, IWPS / categorical |
| Abundance * | Wake zone abundance / continuous |
| Attack rate * | Attacks per minute / continuous |

**Table 2**

| | **UW** *(176)* | **IW** *(164)* | **UWPS** *(155)* | **IWPS** *(155)* | **TOTAL** *(650)* |
|---|---|---|---|---|---|
| Northern fulmar<br>*Fulmarus glacialis* | 171 | 13 | 5 | 0 | 189 |
| Gulls<br>*Larus* spp. | 134 | 14 | 2 | 0 | 150 |
| Short-tailed shearwater<br>*Puffinus tenuirostris* | 37 | 4 | 7 | 1 | 49 |
| Black-legged kittiwake<br>*Rissa tridactyla* | 1 | 0 | 0 | 0 | 1 |
| Laysan albatross<br>*Phoebastria immutabilis* | 1 | 0 | 0 | 0 | 1 |
| Unidentified seabird | 0 | 1 | 2 | 1 | 4 |

**Table 3**

| | **Treatment** | | | | **Behavior** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Surface foragers** *(67% dev; n=494)* | | **Shearwaters** *(74% dev; n=358)* | | **Surface foragers** *(50% dev; n=268)* | | **Shearwaters** *(82% dev; n=198)* | |
| **Variable** | p-value | % dev | p-value | % dev | p-value | % dev | p-value | % dev |
| Month | ns | - | ns | - | ns | - | ns | - |
| Time-of-day | 0.000 | 6% | 0.000 | 10% | ns | - | ns | - |
| lo(location) | 0.000 | 9% | 0.000 | 10% | 0.011 | 10% | 0.000 | 7% |
| lo(depth) | 0.000 | 4% | ns | - | ns | - | ns | - |
| lo(swell) | ns | - | 0.000 | 7% | ns | - | ns | - |
| lo(swell, wind) | 0.005 | 4% | ns | - | ns | - | 0.000 | 9% |
| Sea State | ns | - | 0.000 | 5% | ns | - | ns | - |
| Cloud cover | 0.025 | 2% | ns | - | ns | - | 0.000 | 4% |
| lo(Barometric) | ns | - | ns | - | ns | - | 0.000 | 4% |
| Moon | ns | - | 0.000 | 2% | ns | - | 0.000 | 7% |
| lo(distance from last retrieval) | 0.000 | 5% | ns | - | ns | - | 0.000 | 9% |
| Treatment | **0.000** | **28%** | **0.000** | **14%** | **0.000** | **21%** | 0.000 | 9% |
| lo(abundance) | na | | na | | 0.013 | 7% | **0.000** | **17%** |
| lo(attack rate) | na | | na | | ns | - | ns | - |

**Table 4**

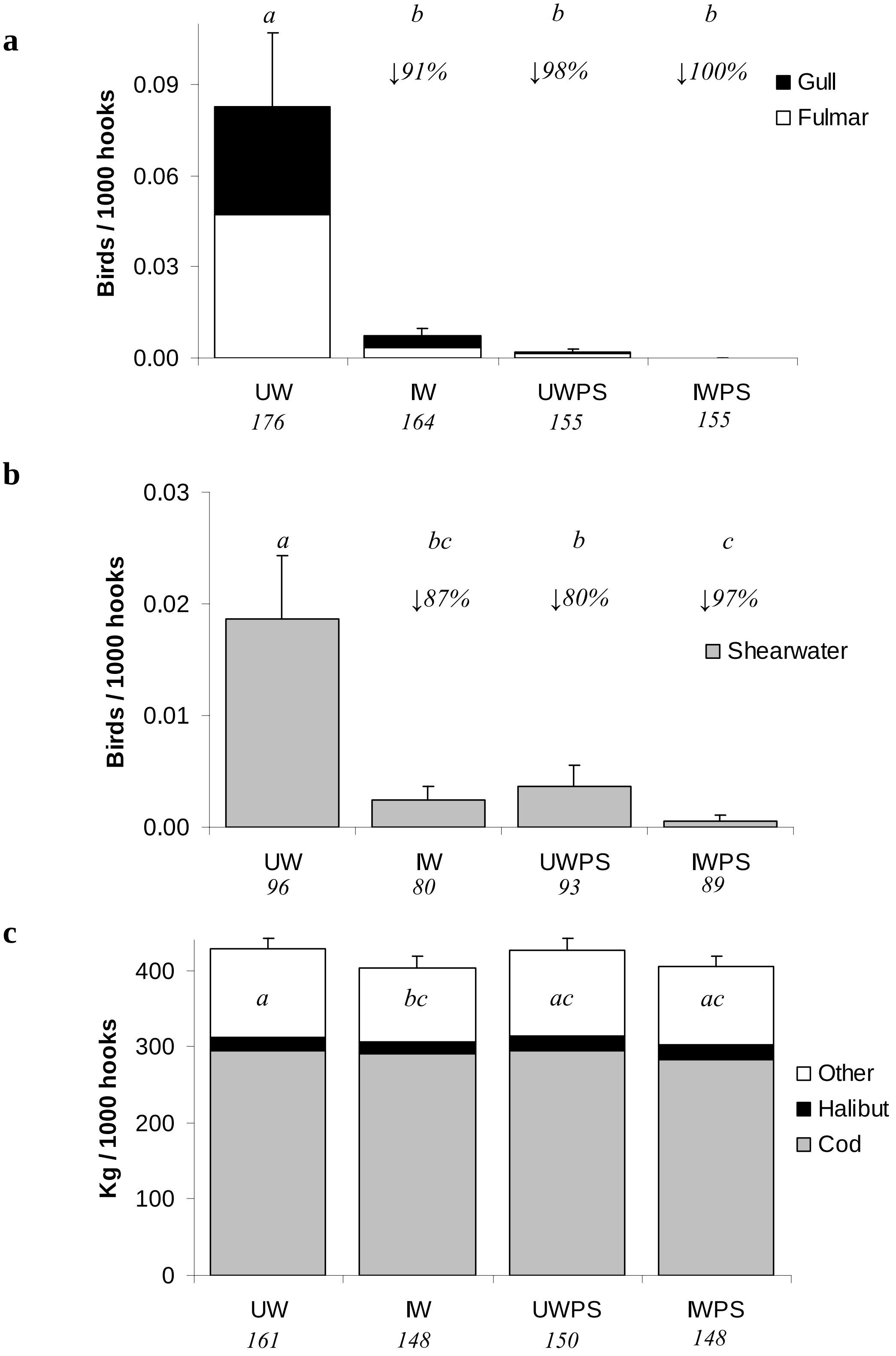
| | **Cod** *(48% dev; n=559)* | | **Halibut** *(51% dev; n=578)* | | **Other bycatch** *(41%dev; n=584)* | |
|---|---|---|---|---|---|---|
| **Variable** | p-value | % dev | p-value | % dev | p-value | % dev |
| Month | 0.000 | 5% | 0.000 | 8% | 0.000 | 7% |
| Time-of-day | ns | - | ns | - | ns | - |
| lo(location) | 0.000 | 5% | 0.000 | 22% | 0.000 | 9% |
| Depth | 0.002 | 1% | ns | - | 0.000 | 3% |
| lo(swell, wind) | 0.000 | 4% | ns | - | 0.037 | 2% |
| Hauling speed | 0.000 | 5% | 0.002 | 1% | ns | - |
| Vessel | 0.000 | 2% | ns | - | 0.000 | 3% |
| % hooks not occupied by halibut | na | - | 0.000 | 4% | na | - |
| **Treatment** | **ns** | | **ns** | | **0.007** | **1%** |

**Table 5**

| Vessel | Gear | N | Seconds | Distance |
|---|---|---|---|---|
| A | UW | 134/15 | 18.0 | 76.0 |
| | IW | 129/16 | 9.6 | 40.5 |
| B | UW | 110/13 | 28.5 | 92.1 |
| | IW | 102/13 | 15.1 | 48.9 |

**Table 6**

| | | | 0-2 meter (m/s) | | | 0-15 meter (m/s) | | | 0-20 meter (m/s) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Vessel** | **Gear** | **N** | **Mean** | **s.d.** | **Range** | **Mean** | **s.d.** | **Range** | **Mean** | **s.d.** | **Range** |
| A | UW | 134 / 15 | 0.13 | 0.06 | 0.06-0.50 | 0.13 | 0.01 | 0.10-0.16 | 0.14 | 0.01 | 0.11-0.16 |
| | IW | 129 / 16 | 0.23 | 0.07 | 0.11-0.50 | 0.24 | 0.02 | 0.15-0.28 | 0.24 | 0.02 | 0.16-0.28 |
| B | UW | 110 / 13 | 0.08 | 0.03 | 0.04-0.17 | 0.11 | 0.01 | 0.10-0.13 | 0.12 | 0.01 | 0.10-0.14 |
| | IW | 102 / 13 | 0.15 | 0.06 | 0.06-0.40 | 0.20 | 0.01 | 0.17-0.22 | 0.21 | 0.01 | 0.18-0.23 |


a
Birds / 1000 hooks
0.00
0.03
0.06
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a
b
b
b
↓91%
↓98%
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■ Gull
□ Fulmar
UW
176
IW
164
UWPS
155
IWPS
155
b
Birds / 1000 hooks
0.00
0.01
0.02
0.03
a
bc
b
c
↓87%
↓80%
↓97%
▨ Shearwater
UW
96
IW
80
UWPS
93
IWPS
89
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Kg / 1000 hooks
0
100
200
300
400
a
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ac
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□ Other
■ Halibut
▨ Cod
UW
161
IW
148
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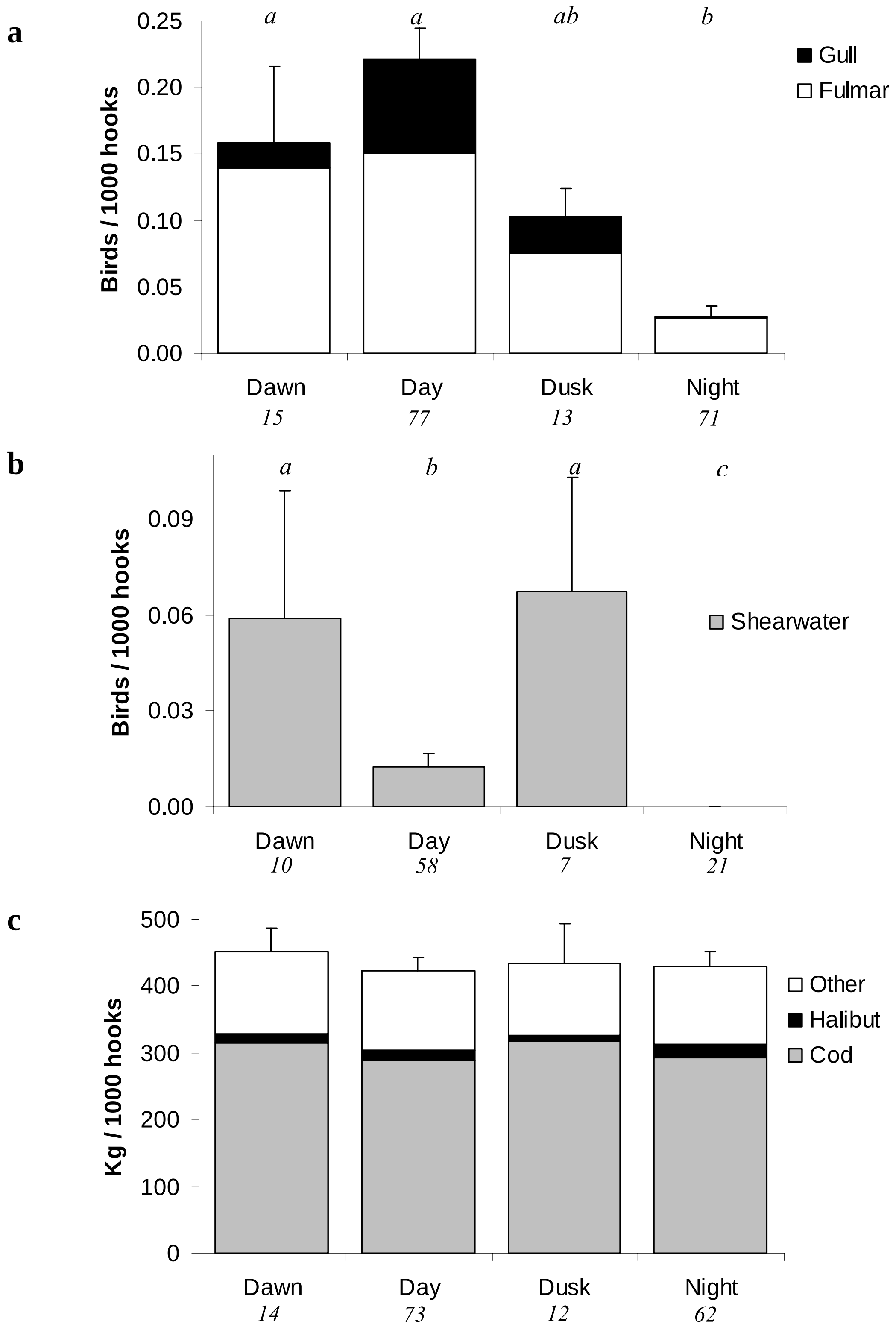
150
IWPS
148

**Figure 1**


a
a
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Gull
Fulmar
Birds / 1000 hooks
0.25
0.20
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Dawn
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Day
77
Dusk
13
Night
71
b
a
b
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c
Shearwater
Birds / 1000 hooks
0.09
0.06
0.03
0.00
Dawn
10
Day
58
Dusk
7
Night
21
c
Other
Halibut
Cod
Kg / 1000 hooks
500
400
300
200
100
0
Dawn
14
Day
73
Dusk
12
Night
62

**Figure 2**

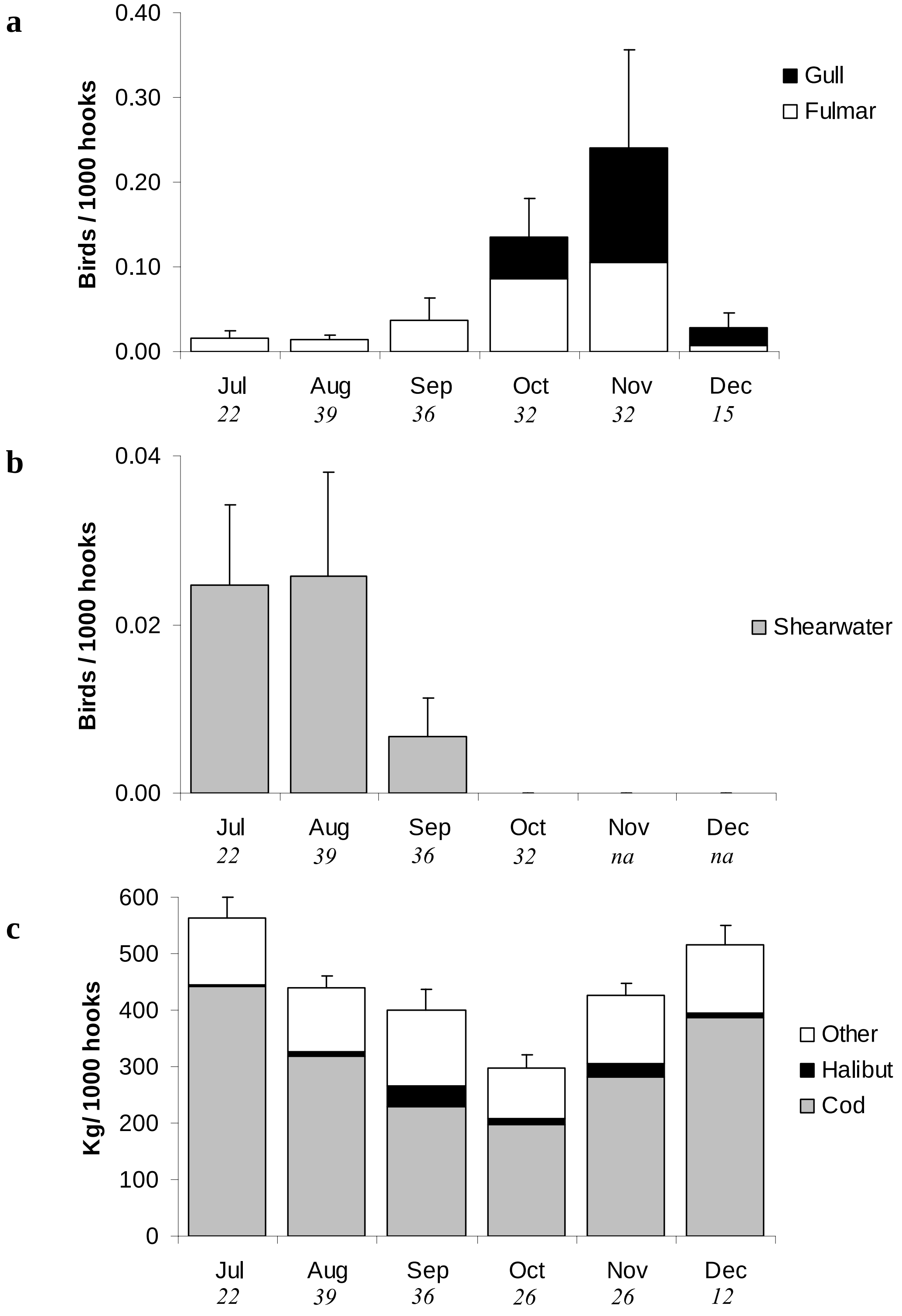

a
Birds / 1000 hooks
0.40
0.30
0.20
0.10
0.00
■ Gull
☐ Fulmar
Jul 22
Aug 39
Sep 36
Oct 32
Nov 32
Dec 15
b
Birds / 1000 hooks
0.04
0.02
0.00
▨ Shearwater
Jul 22
Aug 39
Sep 36
Oct 32
Nov na
Dec na
c
Kg/ 1000 hooks
600
500
400
300
200
100
0
☐ Other
■ Halibut
▨ Cod
Jul 22
Aug 39
Sep 36
Oct 26
Nov 26
Dec 12

**Figure 3**

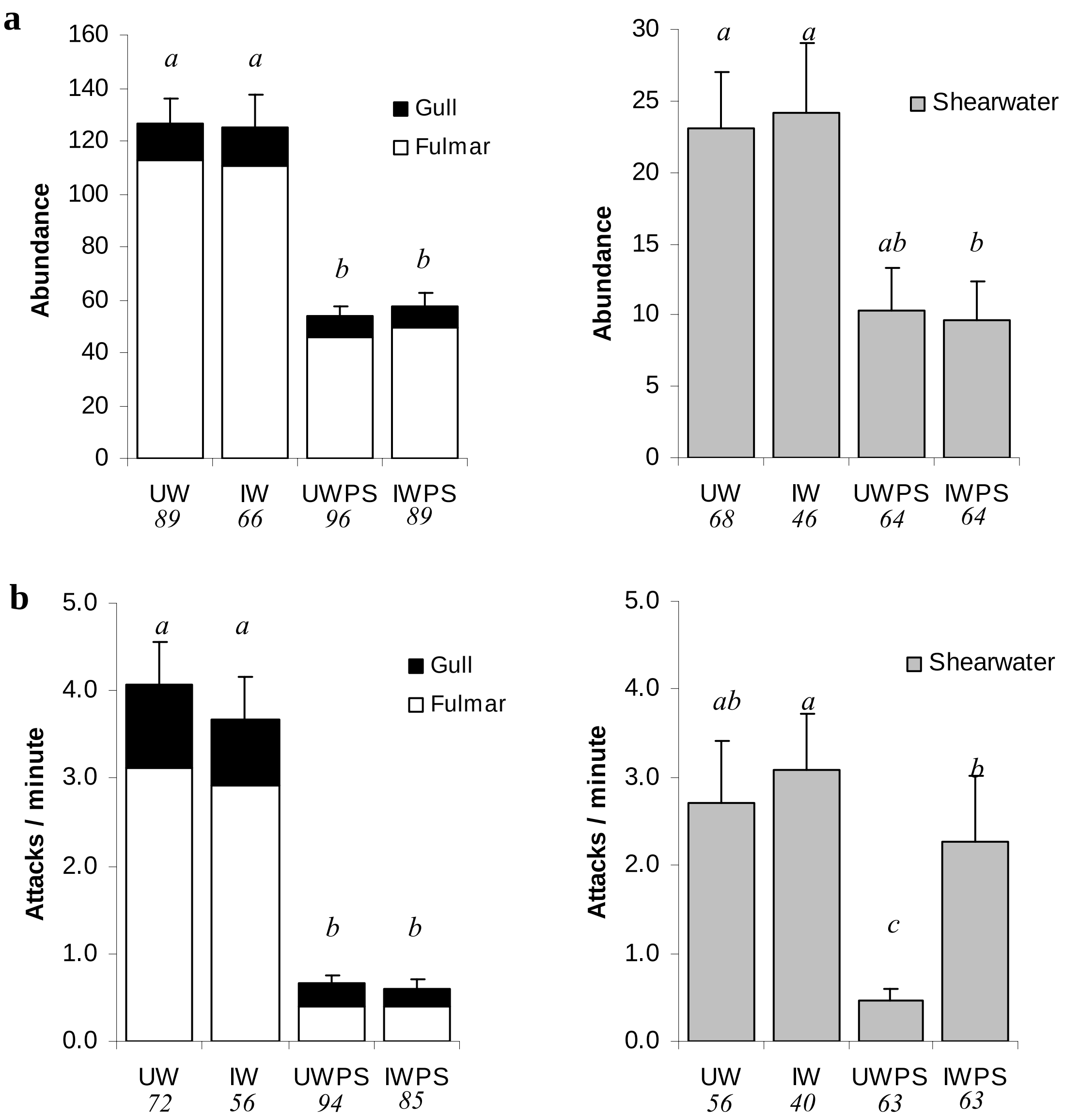

a
160
140
120
100
80
60
40
20
0
Abundance
a
a
b
b
■ Gull
☐ Fulmar
UW
89
IW
66
UWPS
96
IWPS
89
30
25
20
15
10
5
0
Abundance
a
a
ab
b
▨ Shearwater
UW
68
IW
46
UWPS
64
IWPS
64
b
5.0
4.0
3.0
2.0
1.0
0.0
Attacks / minute
a
a
b
b
■ Gull
☐ Fulmar
UW
72
IW
56
UWPS
94
IWPS
85
5.0
4.0
3.0
2.0
1.0
0.0
Attacks / minute
ab
a
c
b
▨ Shearwater
UW
56
IW
40
UWPS
63
IWPS
63

**Figure 4**

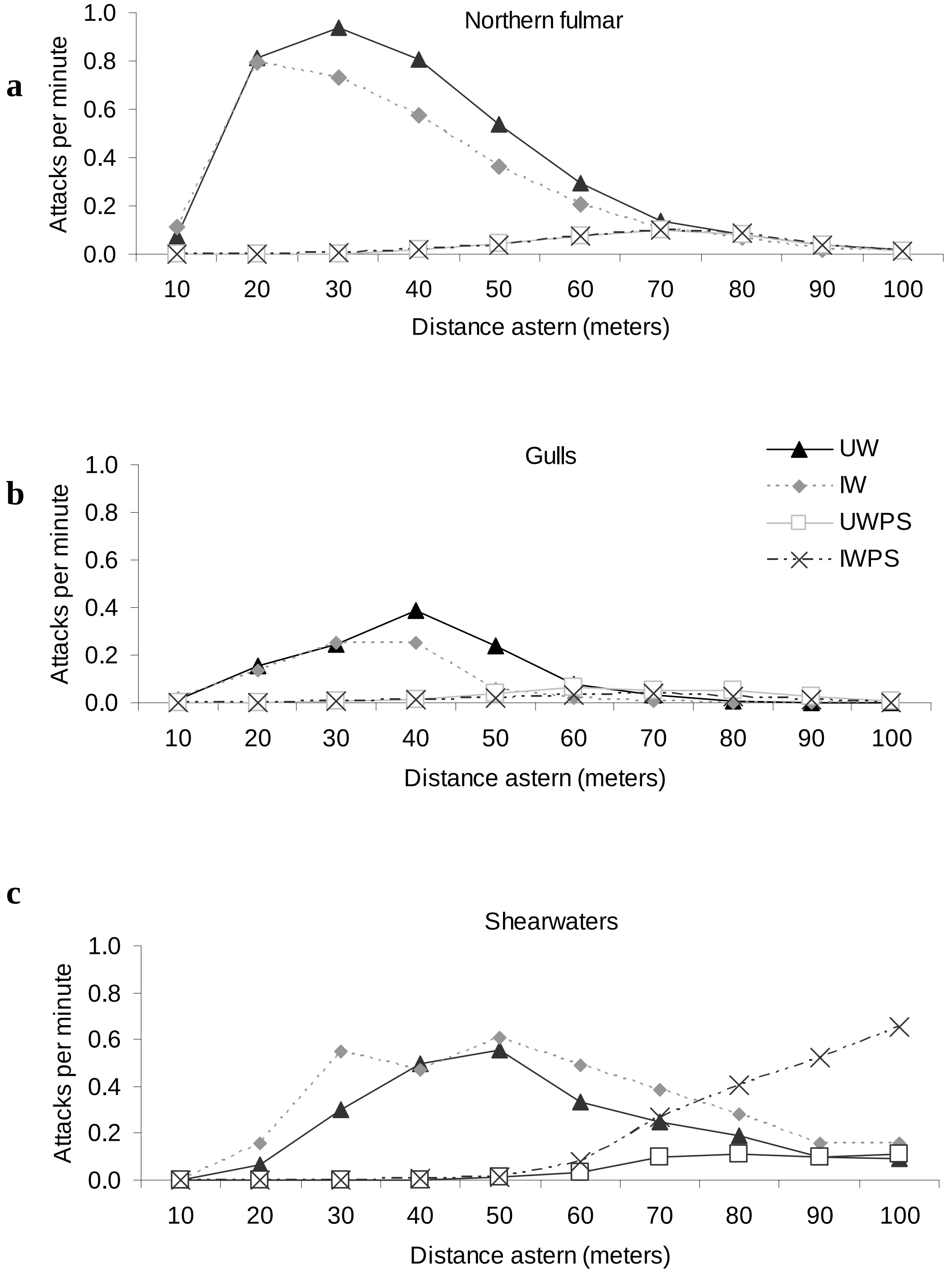
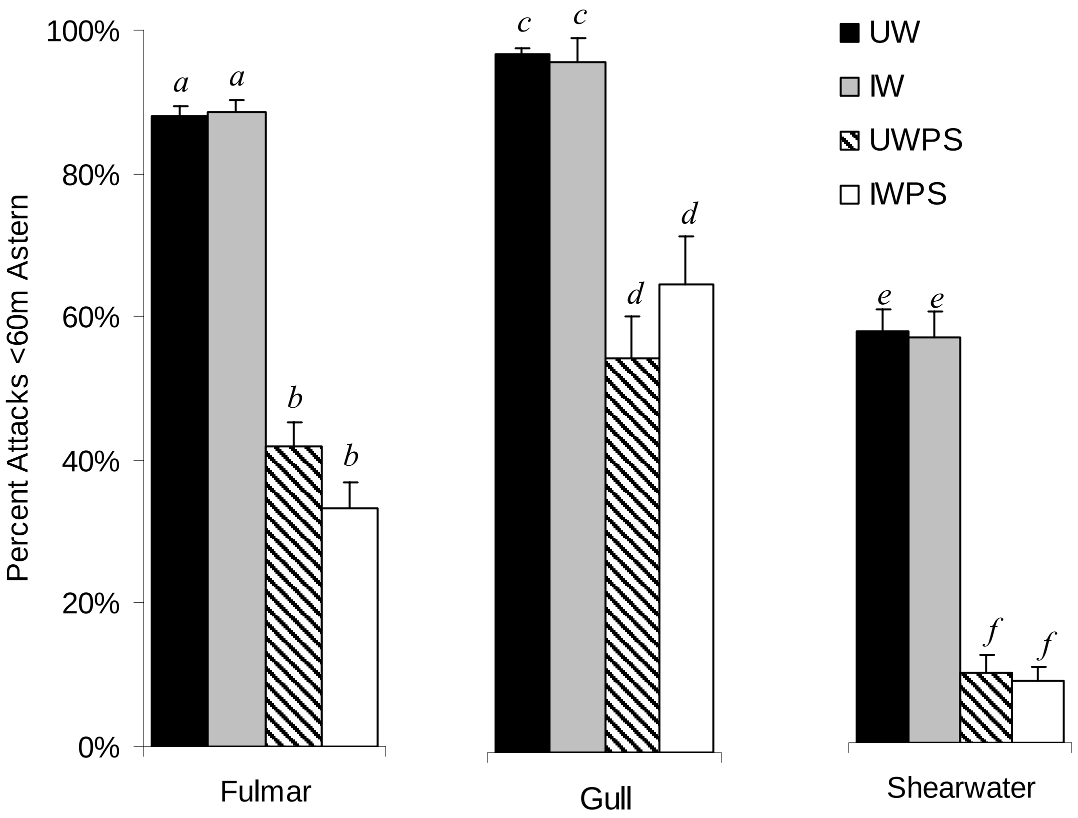

a
Northern fulmar
Attacks per minute
1.0
0.8
0.6
0.4
0.2
0.0
10
20
30
40
50
60
70
80
90
100
Distance astern (meters)
b
Gulls
UW
IW
UWPS
IWPS
Attacks per minute
Distance astern (meters)
c
Shearwaters
Attacks per minute
Distance astern (meters)

**Figure 5**



864
865
866 **Figure 6**

## Supplemental Data – Development of integrated weight groundline in Alaska

### *Methods*

Preliminary testing of the integrated weight concept was performed in 2000 on two vessels during seabird avoidance experiments (Melvin et al. 2001). UW longlines were wrapped with lead wire at one or two hook intervals to mimic integrating weight throughout the line as well as adding 4.5 kg weights every 90 m, the more typical method for adding weight to demersal longlines. In 2002, A.S. Fiskevegn manufactured prototype longlines with 25, 50, 75 and 100 g/m integrated into the line based on these results. These loadings were tested on two additional vessels off Alaska and one vessel in the New Zealand ling fishery (Robertson et al. 2002). Sink rates of all prototype gear were measured with Mk7 time-depth recorders (TDRs; Wildlife Computers, USA) attached midway between weights. TDRs were acclimated to surface sea water temperatures for up to 30 minutes prior to gear deployment to minimize anomalous measurements following protocols described by Robertson et al. (2006).

### *Results*

In the 2000 trials mimicking IW using lead wire, the maximum weighting of 52 g/m sank 1.7 to 2.6 times faster than the traditional UW gear, and 1.6 to 2.2 times faster than the UW with 4.5 kg weights attached every 90 m; Figure S1a). This latter comparison of the IW prototype and attached weights at 90 m intervals (an average of 50 g/m if expressed in similar terms) demonstrates the value of integrated versus attaching weight at longer intervals.

In the 2002 trial of prototype IW weightings, the 75 g/m and 100 g/m lines proved impractical and were eliminated from further consideration. These lines were too heavy for the crew to handle safely, and after one month of fishing, lead began to move to the surface of line tearing rope fibers, especially at the swivel crimps, leading to line breaks as gear was retrieved. The 50 g/m line performed well, coiling consistently on the magazines and passing through the autoline system with fewer difficulties than traditional UW gear. On these vessels, 50 g/m IW sank 1.4 to 1.8 times faster than UW gear, while 25 g/m IW sank 1.2 times faster than UW (Figure S1b). Based on these data and data from Robertson et al. (2002), 50 g/m IW was selected as a strong candidate for an effective seabird deterrent with superior performance in fishing operations.

## Supplemental References

Melvin, E. F., J. K. Parrish, K. S. Dietrich, and O. S. Hamel. 2001. Solutions to seabird bycatch in Alaska's demersal longline fisheries. Project A/FP-7, WSG-AS 01-01, Washington Sea Grant.

Robertson, G., M. McNeill, B. King, and R. Kristensen. 2002. Demersal longlines with integrated weight: A preliminary assessment of sink rates, fish catch success and operational effects. WG-FSA-02/22, CCAMLR, Hobart.

Robertson, G., M. McNeill, N. Smith, B. Wienecke, S. Candy, and F. Olivier. 2006. Fast sinking (integrated weight) longlines reduce mortality of white-chinned petrels (*Procellaria aequinoctialis*) and sooty shearwaters (*Puffinus griseus*) in demersal longline fisheries. Biological Conservation **132**:458-471.

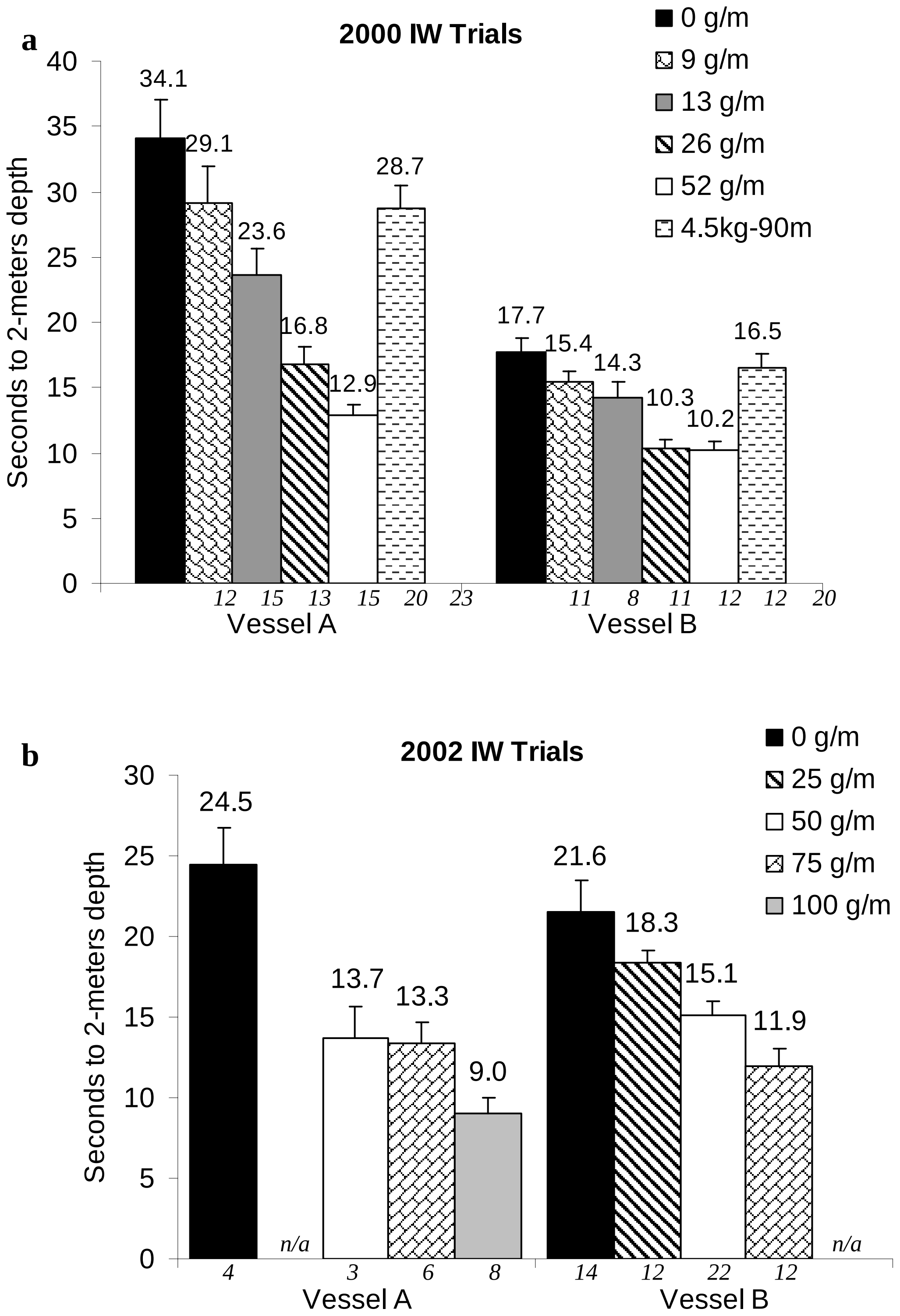


**Figure S1**Mean seconds to 2-meters depth (±SE) of longlines for unweighted (0 g/m) and weighted longlines during 2000 preliminary IW trials (a) and 2002 prototype trials (b). The 4.5 kg weight attached every 90 m (4.5kg-90m) is approximately equivalent to 50 g/m. Sample size (number of sets) shown below bars for each weight regime.