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Shrink and Defend: A Comparison of Two Streamer Line designs in the 2009 South Africa Tuna Fishery

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ABSTRACT

Although pelagic longline tuna fisheries managed by international agreements constitute one of the greatest conservation threats to seabirds of the southern oceans, best mitigation practices for these fisheries, including the best streamer lines design, are the subject of considerable debate. We compared the performance of a "light" streamer line with short streamers to a "hybrid" streamer line that mixes long streamers with short streamers using seabird attack rates in the Japanese joint venture tuna fishery in the South Africa EEZ. We also determine the sink rates of weighted (60 g placed 70 cm from the hook) and unweighted branchlines (status quo) to inform the distance astern that birds have access to baited hooks. Most primary attacks were made by white-chinned petrels and most of those occurred beyond 100 m astern, the target aerial extent of tori lines. A third of primary attacks led to secondary attacks by albatrosses. Virtually all albatross attacks occurred within 100 m. Fewer birds attacked baits inside 100 m when hybrid lines were used, but mean rates were not statistically significant for divers or surface foragers. Unweighted branchlines sank beyond the reach of diving seabirds (10 m) more than 3 times (307 m) further from the stern than did weighted branchlines (~ 100 m). These data strongly suggest that in order to defend baited hooks from bird depredation in a white-chinned petrel dominated system with streamer lines, the distance at which baits sink to 10 m must be reduced to within an achievable streamer line aerial extent.

INTRODUCTION

Pelagic longline fisheries targeting tuna and managed by international agreements (Regional Fishery Management Organizations or RFMOs) constitute one of the greatest conservation threats to Southern Ocean seabirds (CCAMLR 2005). Seabird mortality occurs in longline fisheries when seabirds depredate sinking baits as gear is deployed and become hooked or tangled in a branchline and drown. Additionally, when diving birds retrieve baited hooks they need to bring the bait to the surface and reposition it before they can ingest the bait. This behavior frequently draws attacks from other birds and can result in the hooking or entanglement of a bird other than the one making the initial attack. Through these secondary interactions deeper-diving birds can increase the number of baits available to shallow surface foragers such as albatrosses. Consequently, effective seabird bycatch mitigation must be effective against diving birds, as well as surface foragers. Seabird bycatch mitigation involves sinking baited hooks beyond the reach of seabirds as quickly as possible and preventing seabirds from accessing them until they sink out of reach.

A streamer line, also referred to as a tori line, is a seabird bycatch deterrent developed by Japanese fishermen to protect baits from birds. It consists of a line with streamers that is towed from a high point on the vessel at or near the stern and positioned over the sinking baits as the longline is deployed. As the vessel moves forward drag created by the in-water extent of the tori line lifts the line closest to the vessel yielding an aerial extent. Streamers, typically made of strands of line or plastic tubing, are suspended at regular intervals from the aerial extent. It is the aerial extent with streamers that deters birds. In many fisheries the aerial extent is maximized by towing a device or object to create additional drag. The goal is to maintain the streamer line over the sinking baited hooks in such a way that the streamers prevent seabirds from accessing baits.

Unlike demersal fisheries where all fishing gear sinks below the surface within 50 m of the stern, pelagic longline fisheries deploy long, typically un-weighted branchlines attached to a mainline suspended beneath the surface from surface floats. The potential for fouling surface floats on tori lines makes tori lines more challenging to use in pelagic fisheries. Often fishers deploy tori lines with no towed device thereby reducing the aerial extent and effectiveness; deploy tori lines to the leeward side of the gear where they do little to protect sinking baits; or do not deploy tori lines at all for fear of interrupting the fishing operation by fouling surface floats on the tori line.

Although tori line are the most widely prescribed seabird bycatch technology, the optimal tori line design – length, materials and configuration – and deployment specifications – aerial extent, positioning and number of streamer lines – have not been determined through research for demersal or pelagic longline fisheries (Melvin and Robertson, 2000 and Melvin et al. 2004), consequently best tori line designs and specifications are the subject of debate by fishery managers, seabird scientists, fishers and representatives of the conservation community.

The most adopted tori line is the “conventional” line, which has proved highly successful at reducing seabird bycatch in the CCAMLR and Alaska demersal fisheries. The “conventional” tori line includes long streamers that extend from the backbone of the tori line to the water in the absence of wind. Japan has advocated for the use of “light” tori lines – a specific tori line design that has short streamers (0.5 m) – in high seas tuna fisheries to protect seabirds. Research results on the effectiveness of “light” vs. “conventional” tori lines are inadequate, especially in the southern hemisphere, and in some cases conflicting (ACAP 2008). Available qualitative evidence from the South Africa joint venture tuna fishery suggests that seabird bycatch rates were near ten times higher in years when “light” tori lines were used compared to years when more “conventional” tori lines were used. Given these circumstances, the Agreement for the Conservation of Albatrosses and Petrels (ACAP) Seabird Bycatch Working Group concluded that: “thorough comparative experimental assessment of “light” and “conventional” bird scaring lines needs to be undertaken against Southern Ocean assemblages of diving seabirds (e.g., *Procellaria* sp petrels and *Puffinus* sp. shearwaters) and albatrosses, with research based on larger sample sizes and more transparent methodologies.”

Increasing the sink rate of baited hooks by adding weight to branchlines was also identified as a high priority for research by ACAP (ACAP 2008). Although branchline weighting is required in some domestic fisheries and is among the seabird mitigation options in some RFMOs (WCPFC 2007), serious issues remain over safety, tangling, effect on fish catch rates, and best configurations (mass and proximity to the hook). It was clear from our 2008 work in the South African tuna fishery that baited hooks on unweighted branchlines sank out of the reach of seabirds well astern of the vessel – over 150 m (Melvin et al. 2009). This distance could nearly double if a branchline was set into the vessel’s wake. The likelihood that tori lines can protect baited hooks to 150 m astern is low to negligible. In 2009, several vessels participating in the

South Africa tuna joint venture fishery quickly approached or exceeded their seabird bycatch caps suggesting that the mitigation measures they were using – primarily two tori lines and night setting - were insufficient to prevent seabird mortalities. These events led us to begin considering tori lines and weighted branchlines as an unavoidable pairing if seabird conservation were to be achieved in this and other tuna fisheries operating in the southern oceans.

This report summarizes our research comparing the performance of two tori line designs: the Japanese "light" tori line with short streamers and the Alaska-Japanese "hybrid" line which mixes long and short streamers (Melvin et al. 2009). A secondary objective was to introduce weighted branchlines into the fishery as a seabird bycatch mitigation measure and determine the sink rate of weighted and unweighted branchlines to inform the distance astern that birds have access to baited hooks and require protection with a tori line. We also aimed to gauge the reaction of the fishing master and the crew to using the tori lines and weighted branchlines.

METHODS

Research was carried out from August 4 to September 7, 2009 aboard two tuna longline vessels, the F/V Fukuseki Maru No. 5 and the F/V Wakashio Maru No. 83, participating in the Japanese tuna joint venture fishery in the South Africa EEZ. This research was conducted under a research permit from Department of Environmental Affairs and Tourism, Marine and Coastal Management, Pelagic and High Seas Fishery Management Division and in collaboration with the Federation of Japan Tuna Fisheries Cooperative Associations and with Tuna South Africa. The time period was selected to carry out the research under worst case circumstances – when seabirds are most abundant and aggressive.

The vessels and fishing operations were similar and typical of the high seas tuna fleet. Both set baited hooks using a bait casting machine and a line shooter. The casting machine tossed baits outboard of the wake and under or inside the port tori line and the line shooter delivered the mainline into the water slack (1.4 times faster than vessel speed). Both used whole pilchard (*Sardinops sagax),* mackerel (*Decapterus macerellus*) and squid (*Illex spp.*) for bait. Vessels set 11 to 12 segments of gear with each segment bounded by radio beacons. Each radio beacon segment was made up of 20 gear units each bounded by 0.3 m diameter plastic floats and with 11 and 12 branchlines per unit (Fukuseki and Wakashio, respectively). The Fukuseki deployed 220 branchlines per radio beacon segment and the Wakashio deployed 240, yielding 2,000 to 3,000 hooks per set. Longlines were typically deployed at 9.5 knots speed over ground.

Tori Lines

The "light" tori line was based on Yokota et al. (2008) and the "hybrid" tori line, that mixed features of tori line used in Alaska demersal longline fisheries (Melvin et al. 2001) and the Japanese light tori line, was based on Melvin et al. (2008). The backbones of both tori line lines were 200 m of 7 mm orange polysteel weighing 5.7 kg. At midway in the project the backbone of the hybrid line was changed to 3 mm Amsteel blue in the aerial extent to reduce weight (0.74 kg/100m).

The key differences between the two lines was the length of individual streamers, how far streamers extended along the line away from the stern into the aerial extent, and their weight. The light line streamers were alternating red and yellow 1 m strips of 12.7 mm packing strap material spliced into the backbone and tied at the center to give a two-stranded streamer with

0.5-meter extending from each side. Streamers were placed at one-meter intervals along the backbone to 90 m (Figure 1).

The long streamers of the hybrid line were 15 single lengths of orange 6.4 mm UV protected Kraton® tubing 8.5 to 1.5 m long spaced at 5 m intervals across the 80 m span closest to the stern (Figure 1). A 70 m section followed with yellow packing strap streamers configured identically to those of the light tori line. Our intent was to have streamers that extended to the water across an aerial extent of 150 m. The long streamers were clipped to three-way swivels in the backbone with 8.9 cm snaps. The hybrid line was 2.9 kg heavier than the light line owing to the weight of the streamer tubing (2.9 kg). Our goal was to maximize and match the aerial extent of both lines with a target of 100 m to 150 m.

Two tori lines of the same type were deployed together each set on both vessels. On the port side, tori lines were attached to purpose built, angled davits (tori pole) 10 m tall and 5.1 m forward of the stern. The tori poles were turned 90° outboard moving the tori line attachment point between 3 and 4 meters outboard. The second tori line was attached to a mast positioned on the midline of the vessel 3.5 m forward of the stern at a height of 9 m. In the initial days of the trip, we worked to maximize the heavier hybrid line's aerial extent by experimentally adding road cones, funnels, small buoys, and packing strap streamers to the in-water extent of the backbone to create drag. Adding strips of packing strap to the in-water extent of the backbone proved the best option to create drag and to avoid fouling the tori line on the fishing floats. The typical aerial extent of the heavier hybrid line was increased from approximately 75 - 80 meters to 95 - 100 meters (mean = 95.2, SE = 1.15) by adding three 0.25-meter strips of packing strap material in 0.3 m clusters at 5 m intervals along the last 50 m of backbone. Subsequently, strips of packing strap material were added in the same way to the in-water extent of the light line in order to increase its aerial extent and match that of the hybrid line (mean = 96.3, SE = 1.56).

Branchline Weighting
A subset of branchlines were weighted with 60 g "safe-leads®", the safest known option available for increasing the sink rate of baited hooks and consequently decreasing the distance astern requiring protection with tori lines (Gillman 2008 and Marine Safety Solutions. 2008). Safe-lead are made up of a rubber gasket sandwiched between two leads held in place by two "O" rings forming a squat, spindle-shaped weight. The monofilament portion of the branchline is threaded through a hole in the center of the gasket. Squeezing the release button widens the aperture of the hole allowing the branchline to be threaded through the safe-lead. Releasing the button settles it onto the branchline where the safe-lead maintains its position via 5 kg of pressure. The sudden accelerating force of the recoiling branchline in a flyback overcomes the friction of the gasket allowing the line to slip through the center of the lead, which serves to dampen the leads velocity, thus muting danger to the crew (http://www.fishtekmarine.com/safeleads.php).

The monofilament portion of each branchline was 1.8 mm and 1.9 mm in diameter, well within the 1.6 to 2.2 mm safe-lead specification. Although the manufacturer recommend that safe-leads be placed 2 m above the hook, the fishing masters placed the leads 50 cm from the hook to minimize tangles during line setting. The fishing masters expressed concern that weighted branchlines set with a bait casting machine would results in a "hinge" effect – the weight would lead the bait to the water and while sinking. Fishing masters indicated that they felt this jack-knifing effect would increase the number of tangles and prevent the bait from sinking in a manner that is attractive to fish. Initially crimps were positioned just above the lead to maintain the prescribed distance of 50 cm; however, as fishing proceeded and hooks were replaced, crimps were not. A position of approximately 60 to 70 cm from the hook proved most compatible with the circumference of the branchline coils and became the typical configuration. As branchlines were coiled for storage, crew members repositioned and maintained or replaced safe-leads as needed. The durability of individual safe-leads was not monitored during hauls, however, safe-lead loss was estimated by counting the number of safe-leads remaining on board after the fishing trip.

In response to ongoing deliberations, the fishing master of the Fukuseki proposed branchline weighting concepts he thought would prevent tangles while line setting and be safer than standard leaded swivels. This idea involved attaching two weights via 14 to 22 cm of wire leader. With regard to flybacks, he thought that opposing weights and the wire leader might dampen the flyback speed if the hook were suddenly released. At his urging we measured the sink rate of the three configurations he proposed: one with two 10 g weights, one with a 10g and a 30g weight, and one with a single 30g weight. Approximately ten of each of these configurations were deployed in the final days of the trip to determine their sink rates.

Experimental Design

This research required a departure from the requirement that longlines be deployed exclusively at night (night setting). To allow evaluation of tori line performance using seabird behavior, longline sets extended at least one hour into daylight, thus, a typical set straddled night, dawn and early day with two to three radio beacon segments set in the dawn to day period. To help reduce bias due to environmental factors, each vessel alternated between light and hybrid tori lines each day, while the alternate tori line type was fished simultaneously aboard the opposite vessel. Additionally the vessels coordinated fishing operations and set gear in the same direction typically within sight of each other.

Each vessel was provided 1000, 60g safe-leads. Weighted branchlines were deployed in two of the 10 to 12 radio beacon segments each day. The first safe-lead segment was deployed in the third segment set, and therefore, was set exclusively at night. The second Safe-lead segment was deployed in the third from last segment set to allow researchers to monitor flybacks of at least one weighted segment each haul.

Data Collection

Researcher time was rationed to allow them to monitor the set and the haul, as well as doing periodic sink rate measurements.

Behavioral Observations: Fishery researchers collected data on seabird numbers and seabird attacks on baited hooks during all daylight sets. In all cases, the location (beginning and ending buoy and radio beacon number) within the longline was recorded for each observation. Each observation session began with a 20 minute count of primary attacks by species and secondary attacks as a function of distance astern (horizontal: 0-25 m, 26-50 m, 51-75 m, 76-100m, 101-125m, 126-150 m, and 151 to 200 m) and location relative to the tori lines (lateral: inside the tori lines or to port of (outside) the port tori line; Figure 2). Distance bins were delimited by markers inserted into the tori lines. The first attack rate observation period was followed by an estimate of seabird abundance by species (on the water and in the air) in a 250 m hemisphere centered at the midpoint of the stern. A host of operational and physical data was collected immediately following the abundance estimate (Table 1). Data were also collected on where baited hooks and coils landed relative to the wake and tori line for 10 sequential baits prior to each attack rate sample. Additional attack rate observation periods followed to the extent that time allowed until the set was completed. This procedure usually resulted in 20 minutes between attack rate data collection sessions.

Haul Observations: Researchers observed the retrieval of five to six of the 11 to 12 segments during each haul with the priority of observing the retrieval of all hooks deployed during the dawn-daylight behavioral observations. The number of all catch – fish and birds – was recorded at the species level by radio beacon during the observed portion of the haul. The vessels officers independently recorded the number of target fishes and birds caught by radio beacon throughout the entire haul in the ships logbook. Two seabird counts were conducted each haul using the same protocol as the set – the first one hour after the start of hauling gear and second after haul data collection was completed.

Sink Rates: Star–Oddi time depth recorders (TDRs), model DST Centi-ex, and *SeaStar* software, were used to measure the sink rate of baited hooks with and without weights. TDRs were fixed to the branchline with Tesa tape 70 cm above the eye of the hook – approximately one turn of a branchline coil. The water entry time was recorded for each TDR to the nearest second using a digital wristwatch. Seconds to 2 m, 5 m, and 10 m depths were extracted from each data record and corrected to compensate for the weight of the TDR using the results of static sink rate tests (Data from Graham Robertson, AAD).

Data Analyses

We used a hierarchical approach to compare the magnitude and distribution of seabird attacks between the light and hybrid tori lines. Data were restricted to attack rate sessions that were ≥ 15 minutes and when there were no tori line fouling events leading to an aerial extent less than 80 m (light = 46, hybrid = 21). First we compared the mean aerial extent, the mean rate of attack for all birds, and the mean distance at which birds attacked by foraging guild (diving birds and surface foragers) for the two tori lines using Mann-Whitney U test. To answer the question of whether there are differences in the distribution of attack rates across the seven distance bins in which attacks were recorded for the two tori lines by guild, we used the multi-response permutation procedure (MRPP), a non-parametric method (Mielke 1984, Mielke and Berry 2001, method overviewed in McCune and Grace 2002; implemented with *vegan:mrpp* function (Oksanen et al. 2010) in R; R development Core Team 2009).

To determine if there were differences in the number of attacks inside 100 m vs. outside 100 m for each tori line, we modeled the number of attacks (N) as a function of guild, distance astern, and tori-line type. Because these data are counts, the model used Poisson regression, which is a generalized linear model (glm) with a log-link. That is, attack count (N) is Poisson distributed, and its logarithm can be modeled as a linear function of the independent variables X:

$$\log(E(N)) = a + bX$$

However, because the length of the survey periods varied we modeled the attack rate (attack count per minute), which can also be modeled with Poisson regression by inclusion of an "offset". The "offset" variable is the exposure, i.e., the window of observation over which the counts were made. The coefficient for the offset variable is constrained to be one, so the model becomes:

$$\log(E(N)) = a + bX + \log(ElapsedTime)$$

And, with rearrangement:

$$\log\left(\frac{E(N)}{ElapsedTime}\right) = a + bX$$

Because the attack count data are highly over-dispersed, we used a quasi-likelihood estimation in the generalized linear model. The model was fit in R (R Core Development Team 2009), using the *glm* function following a stepwise approach. Once the null model (intercept and offset term only) was fit each single variable was added to the null model, and deviance and significance (based on the F-test) were evaluated. The variable with the best reduction in deviance was retained. This model became the new 'null model' and was the baseline to which more complex models were compared.

In order to determine if primary or secondary attacks varied between the two tori line types we compared attack rates by guild within the ≤100 m and ≥ 100 m distance bin using a set of Mann Whitney U tests. We also compared the mean attack rates on either side of the port tori line - attacks made between the port and starboard tori (inside) vs. attacks outside of the port tori (outside) - within the ≤100 m and ≥ 100 m distance bins using both tori types and all foraging guilds combined using Mann Whitney U tests. In our analyses of secondary attacks we considered secondary attacks as a measure of primary attacks that were successful at retrieving the baited hook.

Pearson correlation coefficients were used to compare relationships among primary attack rate, the rate of primary attacks that lead to secondary attacks, bird abundance during the set and bird abundance during the haul.

In order to establish the relationship between seabird attacks and seabird mortality, we regressed log transformed seabird catch rate (ln (x+1) where x = number/1000 hooks transformed) on primary attack rate and secondary attack rate (attacks per minute) separately by foraging guild. We compared (non-statistically) the slopes of the two regressions to determine which attack rate was more strongly associated with catch. Data included the first attack rate or abundance session for each day yielding 51 days of data (n = 51).

Two-way analysis of variance (ANOVA) was used to compare the differences in sink rate among our different line weighting scenarios (0, 20, 30, 40, 60 g) and by bait type (sardine, squid, or mackerel scad). Multiple comparisons were made using Tamhane post-hoc tests to evaluate the differences in sinking times to benchmark depths of 2 m, 5 m, and 10 m.

We used Wilcoxon Signed Ranks tests to evaluate the effect of weighted branchlines on target fish catch (tuna and swordfish). Fish catch on weighted segments were matched with one of the two adjacent gear segments selected at random for the paired comparison. Separate tests were performed for safe-lead segments deployed in complete darkness and for segments deployed near nautical dawn.

Mann-Whitney U Test, Pearson correlations, ANOVA, and Wilcoxon Signed Rank tests were run using SPSS for Windows, Release 12.0.0. 2003. Chicago: SPSS Inc.

RESULTS

Seabird Mortality
Seabird mortalities totalled 129 birds (Table 2). Overall, 53% were white-chinned petrels (WCPE) and 43% were albatrosses or giant petrels. Black-browed albatross (BBAL) and shy albatross (SHAL) accounted for most albatross mortalities, but a yellow nosed (YNAL) and a Southern royal albatrosses were also caught. Fewer birds (34%) were caught at night (before nautical dawn) than during the day.

Seabird Abundance
Twenty-seven seabird species attended the vessels. WCPE were by far the most abundant bird during line setting and line hauling averaging just over 50 birds per observation (Table 2). CAPE, BBAL, YNAL and SHAL were the most abundant surface foraging birds. With minor exception, bird numbers by species during the haul were at least two times the number of birds during the set and five species were observed only during line hauling.

Attacks on Baited Hooks - General
Only eight species attacked baited hooks. A total of 818 primary attacks were recorded over the course of 111 attack rates surveys over 30 fishing days on the two vessels. Overall the mean attack rate of diving birds (0.37 attacks per minute) was an order of magnitude higher than that for surface foraging birds (0.04 attacks per minute). WCPE, capable of diving to at least 12.5 m (Huin 1994), made most (77%) primary attacks, attacking on average at a rate of 0.32 attacks per minute. Attacks by other species were at least an order of magnitude lower that that of WCPE. Included were BBAL (8%) CAGN, (8%), and YNAL (2%). CAPE were ubiquitous throughout the study but made no primary attacks probably because they cannot consume a whole fish or squid. Roughly a third of primary attacks (264) led to secondary attacks. Although recording the species making secondary attacks was not part of our protocol, researchers reported that virtually all of the secondary attacks included albatrosses.

Attacks on baited hooks – Tori Line Comparisons
The mean aerial extent for each tori line type was statistically similar (Light = 95.2, Hybrid = 96.3, $p = 0.764$). The mean total attack rate overall for each tori line design was similar (Light = 0.37 vs., Hybrid = 0.25, $p = 0.09$), but the distance astern at which birds attacked differed by foraging guild (Figure 2). Describing patterns in Figure 3 in simple terms, diving birds attacked baits further astern in response to both tori line types (light mean=117.27 m; hybrid mean = 136.94 m) than did surface foraging birds (light mean = 68.8 m and hybrid mean = 81.8 m) and the hybrid line pushed the mean distance of attacks further from the stern for divers and surface birds (20 m and 13 m, respectively). The hybrid line precluded attack by divers within 50 m and allowed relatively few attack from 51 to 75 m, while the light line allowed attacks throughout the seven distance bins monitored. Surface foragers attacked bait almost exclusively within 100 m for both tori line types. The hybrid line excluded attacks by surface foragers in the 0-25 m bin while the light line allowed attacks in all bins within 100 m. Despite visual differences in attack rates across the area monitored, the MRPP testing the difference in the distribution of attack rates for the two tori line types across the 7 distance bins was not significant for either guild ($p = 0.40$).

Collapsing distance bins to inside and outside 100 m, our GLM with tori line type, foraging guild and the two 100 m distance bins as factors explained 29% of the null model deviance.

The number of attacks varied significantly by guild ($p \leq 0.01$), and distance ($p \leq 0.05$), but not by tori line type ($p = 0.17$; Table 3). Significantly more surface forager attacks occurred within 100 m of the stern than outside, while the opposite pattern was true for diver attacks. Though primary attacks occurred at twice the rate inside 100 m for the light line vs. the hybrid line, differences were not statistically significant for either foraging guild (divers: $p = 0.21$; surface foragers: $p = 0.27$; Table 4).

In general, the distribution of secondary attacks across the seven distance bins mirrored those of primary attacks (Figure 3) and like primary attacks, differences in mean rates of secondary attacks were not statistically significant for either foraging guild (divers: $p = 0.18$; surface foragers: $p = 0.77$; Table 4).

Looking at the lateral dynamics of attacks relative to the port tori line and ignoring guild and tori line type, within 100 meters mean primary and secondary attack rates were dramatically higher to port of (outside) the port tori line than inside the two tori lines (primary: outside = 0.12 and inside = 0.06, $p = 0.007$; outside = 0.04 and inside < 0.01, $p = 0.012$; Figure 4). Beyond 100 m the opposite was true for primary attacks but not for secondary. Primary attacks were 6 time higher inside vs. outside (outside = 0.02 and inside = 0.13, $p = 0.008$; Figure 4) while secondary attacks were similar (outside = 0.02 and inside = 0.04, $p = 0.08$; Figure 4)

Mortality and Bird Attacks

Species-specific attack rates did not reflect species-specific mortality rates. WCPE accounted for only 53% of mortalities yet were responsible for most primary attacks. The opposite was true for the albatrosses. They accounted for only 18% of primary attacks, but 40% of mortalities. This phenomenon was most extreme for SHAL for which we saw only one primary attack, but 16 were killed. These data suggest that most albatross mortality is a function of secondary attacks on baits returned to the surface by WCPE, and that controlling seabird bycatch in this fishery will require eliminating WCPE attacks.

Regressions of seabird catch rates on primary and secondary attack rates were both statistically significant (Figure 5 and Table 5); however, the regression on the secondary attack rate produced a much better fit as evidenced by a doubling of the R^2 value, and a substantial (28%) reduction in AIC value. In addition, the magnitude of the slope for the secondary attack rate was over three times that of the primary attack rate. Consequently, there is a much higher expected mean catch rate per secondary attack than per primary attack. Correlation tests comparing bird catch, primary attack rate, and secondary attack rate bird abundance, during the set or during the haul respectively, were not significantly different (Table 6). This result suggests that abundance counts – even when conducted during the set – are a poor proxy for bird mortality or the rate of attacks made on baited hooks.

Weighted vs. Unweighted Branchlines

Bird catch rates were higher on unweighted branchlines (0.973/1,000 hooks; 127 birds) than on weighted branchlines (0.069 birds/1,000 hooks; 2 birds). Both birds caught on weighted branchlines were diving birds (a white-chinned petrel during daylight and a cape gannet near dawn) taken during two different days aboard one vessel in calm weather conditions while using both tori line designs. Fish catch was not statistically different comparing branchlines with and without added weight during sets made exclusively at night ($p = 0.12$) or for sets made near dawn ($p = 0.90$; Table 7). Two crew members were injured when the hooks on weighted branchlines pulled out and flew-back as a fish was being hauled. One of the two injuries was clearly due to the presence of a lead on the branchline. Both injuries had the potential to be serious; however, both crew members recovered and returned to their duties. No injuries were observed during the hauling of unweighted branchlines. In a total of 62 fishing days, 1,114 safe-leads of the original 2,000 were lost or broken (39 leads/1,000 hooks).

Sink Rates to Benchmark Depths
The sink times of unweighted branchlines and branchlines weighted with four different weightings varied significantly to all benchmark depths (2 m, 5 m, and 10 m; Table 8). In post-hoc tests all weightings, with the exception of 20 g to 2 m, sank faster than unweighted branchlines. In general and with few exceptions, increased weighting also dramatically reduced variation in sinking speed as evidenced by 95% confidence intervals. Branchlines with 60 g weights sank fastest and with the least variation to all depths and cut the distance at which birds have access to baits to just under 100 m – the target aerial extent of tori lines and 1/3 that of unweighted lines (307 m; Figure 6).

On two occasions baited hooks with TDRs attached to unweighted branchlines were captured and brought to the surface by birds. The first bait, sinking at 0.16 m/s, was initially captured at 9.1 m, approximately 254 m astern of the vessel. The second, sinking at 0.14 m/s, was captured at 5.2 m, approximately 156 m astern. The birds were not hooked during either event. One bait was brought to the surface and one was not.

DISCUSSION
In our comparison of the hybrid tori line (with long and short streamers) with the light tori line (only short streamers), difference in mortality rates, overall attack rates, and all measures of attack rate by distance were not statistically significant between the two lines. However, there were substantial and important difference in the performance of these lines that were not detected using statistical approaches. That attacks by divers were excluded within 50 m of the stern and by surface foragers out to 25 m astern when the hybrid line was used, and mean diver and surface forager attacks rate within 100 m were half that of light lines suggest superior performance by the hybrid line within the 100 m aerial extent. The lack of statistical significance could be an artefact of sample size.

Our analysis of attacks laterally and horizontally was revealing. That most attacks within 100 m occurred outside the port tori lines for both tori line designs strongly suggests two things: 1) that the port tori pole must place the port tori line further to port to reduce attacks, and 2) that two tori lines are more effective than one. We assume that secondary attacks are a good proxy for successful attacks – a dive resulting in a bait – and that primary attacks result in proportional number of secondary attacks. However, a disproportionately lower number of secondary attacks were recorded inside the port tori line and outside 100 m astern even though there were dramatically higher number of primary attacks there. This result strongly suggests that attacks beyond 100 m were less successful than those made closer to the vessel and that birds displaced further from the stern are less likely to be hooked (Dietrich et al. 2008).

Despite our best effort to have an equal numbers of deployment for each line, the hybrid line fouled more often on surface floats in the stormy conditions in which this study took place leaving half as many complete deployments of the hybrid line (12) vs. the light line (24). Researchers spent a considerable amount of time working with fishing masters and crews to develop ways to create drag in the in-water extent of tori lines while minimizing tori line fouling with surface floats. The importance of reducing tori line fouling events cannot be overstated. At an operational level, gear fouling leads to time lost untangling lines – often in the dark – as well as frustration and extended hours for a tired crew. In some cases fouling can cause the mainline to break resulting in lost gear and fish that are never recovered. For birds, baited hooks are left exposed until a tori line can be replaced. Preventing tori line fouling events while creating sufficient drag to create tori line aerial extents of 100 m or more remains the greatest challenge to making tori lines widely acceptable in pelagic longline fisheries. One option to reduce foulings is to configure floats and the lines connecting floats to the mainline in a way to make them less likely to snag on lines. This might be accomplished by making the upper two meters of the float line less flexible by using a stiff-lay line or by covering the line in a rigid material. We were optimistic that floats could be released well away or down-current from tori lines, but that proved impossible in the turbulent seas we encountered.

Based on this experience we propose that the optimal tori line is one that includes short streamers throughout the aerial extent coupled with long streamers but fewer long streamers than the 15 of the hybrid line used in this study. By using fewer streamers the overall weight of the tori line is reduced, thus reducing the amount of drag needed to maintain a 100 m aerial extent. Specifically, long streamers should extend along the span running from 10 m to approximately 50 from the stern. We also recommend that a "sweeper" streamer that extends to the water be placed on the port tori line forward of the stern. The sweeper would protect the area forward of the zone where the baits typically land in the water during line setting. In conditions where the vessel is setting into the wind without the sweeper streamer, birds flying aft along the port side of the vessel can attack baits as they land in the water without encountering the tori line. An alternative would be to position a boom with streamers (bird curtain) forward of the stern to protect this area.

Based on these results the need to shrink the area astern of the vessel where birds have access to baits (to a depth of 10 m) is compelling. We found that baited hooks on unweighted branchlines sank to our 10 m benchmark depth at over 300 m of the stern (Figure 6). We also found that more attacks occurred beyond 100 m astern – beyond the aerial extent of streamer lines – suggesting that tori lines in a system dominated by WCPE may not be "preventing" attacks by diving birds but rather may be simply "displacing" them further away from the vessel where they still have access to baits. Evidence that seabirds reached baits to a depth of at least 9.2 m confirms our belief that an effective seabird mitigation strategy must protect baits to a depth of at least 10 meters. Finally, we show that in this system albatross mortality is a largely a function secondary interactions –diving birds bringing baited hooks to the surface – especially in the case of SHAL for which we observed only one primary attack but 19 mortalities.

Our data suggest that this bird access window could be reduced to 100 m using 60 g weights positioned within 1 m of the hook. If this weighting were to be applied in this fishery, a tori line with an aerial extent of 100 m could protect the entire area that birds have access to baits, thus maximizing the effectiveness of both the tori lines and the weighted branchlines at reducing seabird bycatch. Sinking baits within 100 m would also allow for tori lines to be shorter – perhaps as short as 125 m – which would likely reduce the number of fouling events with surface floats because there would be less line in the water for floats to catch on.

Branchline weighting was shown to have no effect on target fish (tuna and swordfish) catch rates but this result may not be definitive due to the relative small sample sizes and the short duration of the test; however, it does suggest that fears of branchline weighting reducing fish catch may be unfounded. In this study, safe-leads were lost in two ways: by bite offs or they would break apart when "O" rings failed. Although the loss rates of safe-leads was higher than anticipated, this result was at least partly due to fishing masters electing to position leads within 1 m of the hook where the were likely to be lost when a bite-off occurred. Safe-lead loss due to breakage of individual safe-leads occurred but was not quantified. The manufacturer is addressing this issue by replacing the rubber "O" rings that hold the two halves of the lead together with stainless steel rings. In terms of safety issues, two injuries did occur from weighted branchlines vs. none for unweighted lines, but it is reasonable to believe that more injuries would have occurred with standard weighted swivels than with safe-leads.

Seeing the increased momentum toward branchline weighting to achieve seabird conservation and to avoid exclusion from the fishery when seabird mortality caps are reached, fishing masters are starting to advance new ideas for safer branchline weighting alternatives. These ideas should be tested in shoreside simulations to determine their safety relative to safe-leads and standard leaded swivels before they are tested in large-scale experiments at sea.

Based on this work we conclude that in WCPE dominated systems such as the South Africa EEZ that seabird conservation can only be achieved if the area in which birds have access to baits is reduced with line weighting (or some other method) to the area that can be spanned by the aerial extent of a tori line – shrink and defend. Night setting, adequate and safe branchline weighting, proper deployment of two tori lines with a mix of short and long streamers, and the port tori line deployed further to port, are likely to achieve seabird conservation while allowing vessel to fish with little chance of exceeding bird bycatch limits.

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Table 1. Data collected daily for each attack rate and seabird abundance data collection session during line setting in daylight.

Wind Direction
Wind Speed
Water Temperature
Beaufort Sea State
% Cloud cover
Swell Height
Maximum Visibility
Latitude
Longitude
Course
Vessel Speed
Barometric Pressure
Tori Line Type
Towed Device
Total Tori Line Length
Aerial Extent
Distance of first streamer from the stern

Table 2. Mean seabird abundance during haul sampling, set sampling and confirmed mortalities by common name, species name, foraging guild (diver or surface forager) and vulnerability to longline hooking.

Species	Scientific Name	Guild	Haul Mean	Set Mean	Attack Rate	Mortalities
White-chinned petrel	*Procellaria aequinoctialis*	D	51.78	50.76	0.32	69
Cape petrel*	*Daption capense*	S	38.00	24.09	~	0
Black-browed albatross	*Thalassarche melanophrys*	S	34.05	16.62	0.03	32
Yellow-nosed albatross	*Thalassarche* sp.	S	16.38	7.07	0.01	1
Shy albatross	*Thalassarche cauta*	S	10.33	5.40	< 0.01	19
Wilson's storm petrel*	*Oceanites oceanicus*	S	5.49	0.47	~	0
Cape gannet	*Morus capensis*	D	2.07	1.31	0.03	4
Antarctic prion*	*Pachyptila desolata*	S	1.69	0.29	~	0
Antarctic skua	*Stercorarius antarctica*	S	1.67	0.11	< 0.01	1
Sooty shearwater	*Puffinus griseus*	D	1.24	0.02	~	0
Northern giant petrel	*Macronectes halli*	D	0.76	0.20	< 0.01	2
Soft-plumaged petrel*	*Pterodroma mollis*	S	0.73	0.13	~	0
Wandering albatross	*Diomedea exulans*	S	0.73	0.07	~	0
Southern giant petrel	*Macronectes giganteus*	S	0.51	0.13	~	0
Great-winged petrel*	*Pterodroma macroptera*	S	0.56	0.04	~	0
Northern royal albatross	*Diomedea sanfordi*	S	0.22	0.09	~	0
Grey petrel	*Procellaria cinerea*	D	0.18	0.05	< 0.01	0
Southern royal albatross	*Diomedea epomophora*	S	0.18	0.04	~	1
Giant petrel	*Macronectes* sp.	S	0.13	0.07	~	0
Arctic tern*	*Sterna paradisaea*	S	0.11	0.05	~	0
Great shearwater	*Puffinus gravis*	D	0.07	0.09	~	0
Kelp gull	*Larus dominicanus*	S	0.13	~	~	0
Black-bellied storm petrel*	*Fregetta tropica*	S	0.07	~	~	0
Southern fulmar	*Fulmarus glacialoides*	S	0.04	0.04	~	0
Blue petrel*	*Halobaena caerulea*	S	0.05	~	~	0
Grey-headed albatross	*Thalassarche chrysostoma*	S	0.04	~	~	0
Sooty albatross	*Phoebetria fusca*	S	0.04	~	~	0

* Considered not vulnerable to long line operations and was removed from abundance analyses

Table 3. Generalized linear model of the number of attacks as a function of guild, distance astern, and tori-line type. The model used Poisson regression, which is a generalized linear model (glm) with a log-link. Significance codes: '**' 0.01 '*' 0.05 '.' 0.1 'Dispersion parameter for quasi family taken to be 6.25388. Null deviance =1339.15 on 267 degrees of freedom. Residual deviance = 958.92 on 264 degrees of freedom

Coefficients	Estimate	Std.	Error	t value	Pr(>|t|)
(Intercept)	-1.6539	0.1566	-10.561	< 2e-16	***
guildsurf	-4.8481	1.7752	-2.731	0.00674	**
distanceLT100	-0.6434	0.2668	-2.411	0.01657	*
guildsurf:distanceLT100	3.9206	1.821	2.153	0.03223	*

Table 4. Mean primary and secondary attack rate by foraging guild for light and hybrid tori lines at ≤ 100 m and ≥ 100 m from the stern of a longline vessel. Z is the Mann Whitney U statistic and p is the probability of significance at alpha = 0.05

Guild	Distance	Primary Attacks						Secondary Attacks					
		Light (n = 50)		Hybrid (n = 25)				Light (n = 50)		Hybrid (n = 25)			
		Avg	SE	Avg	SE	Z	*p*	Avg	SE	Avg	SE	Z	*p*
Diving	< 100 m	0.13	0.018	0.07	0.013	-1.25	0.21	0.04	0.005	0.03	0.006	-0.78	0.44
	> 100 m	0.21	0.029	0.28	0.057	-0.56	0.57	0.05	0.007	0.14	0.028	-1.34	0.18
Surface	< 100 m	0.05	0.007	0.02	0.004	-1.10	0.27	0.01	0.001	0.01	0.001	-0.29	0.77
	> 100 m	0.00	0.000	0.00	0.000	-0.50	0.61	na	na	na	na	na	na

Table 5. Statistics for linear regression of ln (seabirds/1,000 hooks + 1) on the primary and secondary attack rates of all birds. Secondary attacks are primary attacks the end in other birds competing for the baited hook when it is brought to the surface. AIC = Akaike information criterion.

Independent Variable	Slope	Adjusted R2	F-statistic	df	p-Value	AIC
Primary Attack Rate	0.484	0.2356	16.41	1, 49	0.000182	70.45
Secondary Attack Rate	1.64	0.4833	47.77	1, 49	9.00E-09	50.48

Table 6. Pearson correlation coefficients comparing bird counts (set and haul) to bird catch, primary attack rate, and the rate secondary attacks.

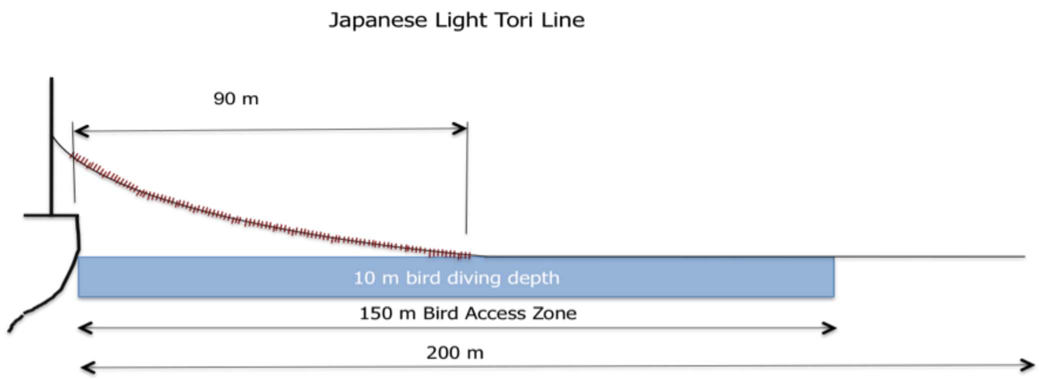
	Set Abundance		Haul Abundance	
	r	*p*	r	*p*
Catch	0.23	0.11	0.08	0.60
AR	0.25	0.08	-0.02	0.87
SAR	0.19	0.19	-0.03	0.85

Table 7. Mean catch rates of fish (tuna and swordfish) per 1,000 hooks for weighted (60 g 70 cm from the hook) and unweighted branchlines. Z = Wilcoxon Signed Ranks Test statistic. P = significance at alpha = 0.05. (need sample size in thousands of hooks)

Time of Day	Mean	SE	Lower 95% CI	Upper 95% CI	Z	P
Night SL	0.0157	0.0031	0.0096	0.0219		
Night	0.0173	0.0027	0.0119	0.0227	-0.1554	0.12
Dawn SL	0.0118	0.0031	0.0057	0.018		
Dawn	0.0114	0.0028	0.0059	0.017	-0.121	0.9

Table 8. Two-way ANOVA of seconds to three benchmark depths (2 m, 5 m, and 10 m) and 95% confidence intervals with Tamhane Post Hoc Multiple Comparisons. Letters indicate significant post-hoc groupings.

		2 m			5 m			10 m		
Weight	n	Sec	Sig	95% CI	Sec	Sig	95% CI	Sec	Sig	95% CI
0	45	14.9	a	5.8	35.1	a	10.5	61.8	a	12.7
20	9	9.6	ab	11.9	21.9	b	12.1	41.6	b	12
30	10	7	bc	3.2	17.4	b	4.9	34.6	b	5.5
40	10	6.4	b	5.2	14.9	bc	8.5	31.1	b	9.9
60	18	4.3	bc	1.1	9.6	c	1.8	19.4	c	2.8
		F Stat	*p* - Value		F Stat	*p* - Value		F Stat	*p* - Value	
Weight		7.68	< 0.0001		14.087	< 0.0001		24.501	< 0.0001	
Bait		0.156	0.856		0.138	0.871		0.163	0.85	



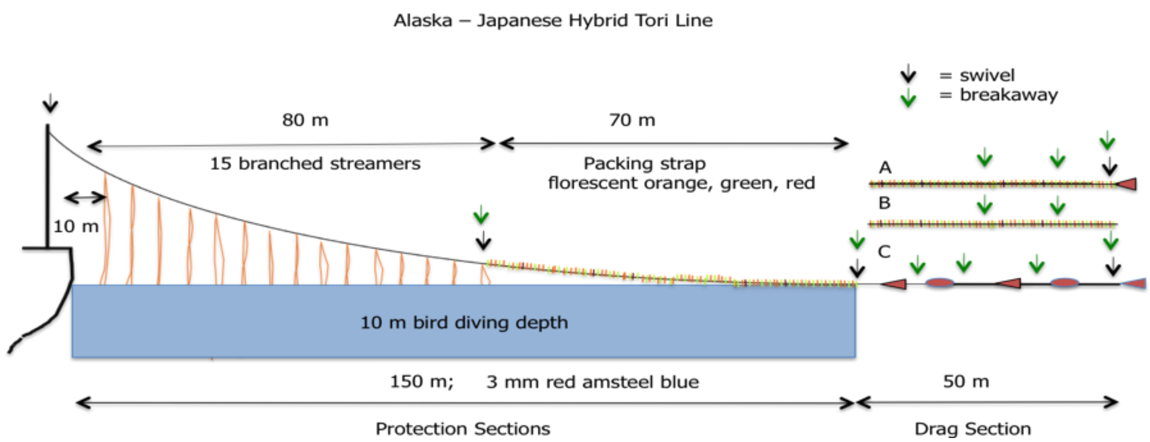


Figure 1. Schematics of tori lines. Light tori line (above) and hybrid tori line (bottom). Bird access zone is the distance astern baited hooks are above 10 m depth which was assumed to be 150 m for unweighted branchlines.

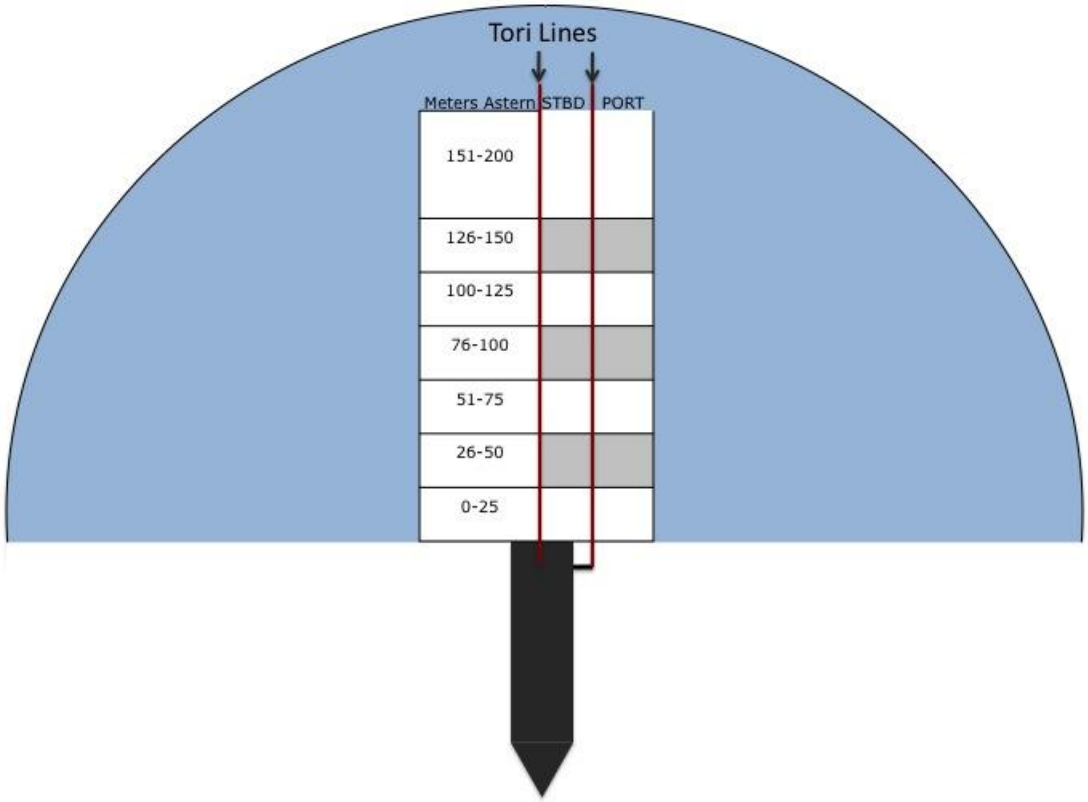


Figure 2. Distance bins (m) relative to starboard and port tori lines for attack rate data collection. Baited hooks were set on the port side between the wake and port tori line. Seabird abundance was estimated in a 250 m hemisphere centered at the stern during line setting and line hauling.

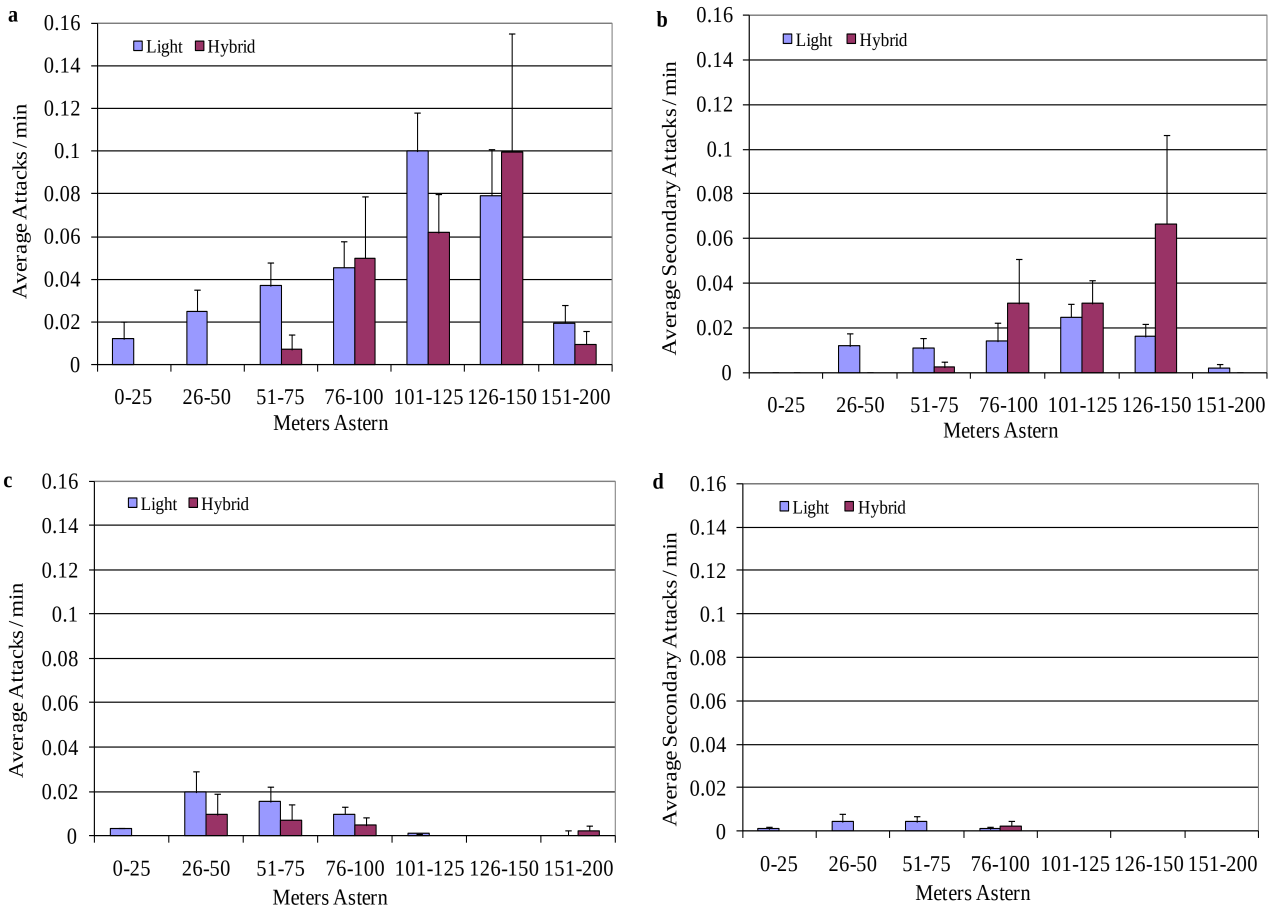


Figure 2. Distribution of primary attacks (left) and primary attacks that lead to secondary attacks (right) for diving (top) and surface foragering (bottom) seabirds in response to two tori line designs (light and hybrid) as a funtion of distance astern to 200 m. Error bars are standard errors.

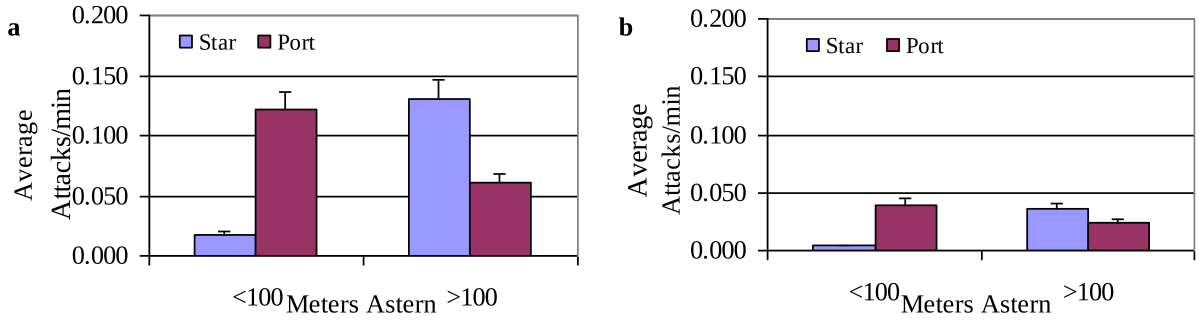


Figure 3. Distribution of average primary attacks (a) and primary attacks that lead to secondary attacks (b) that occurred under the aerial extent (0 - 100 m) and beyond the aeriel extent (101 – 200 m) for pooled seabird guilds . Error bars are standard errors.

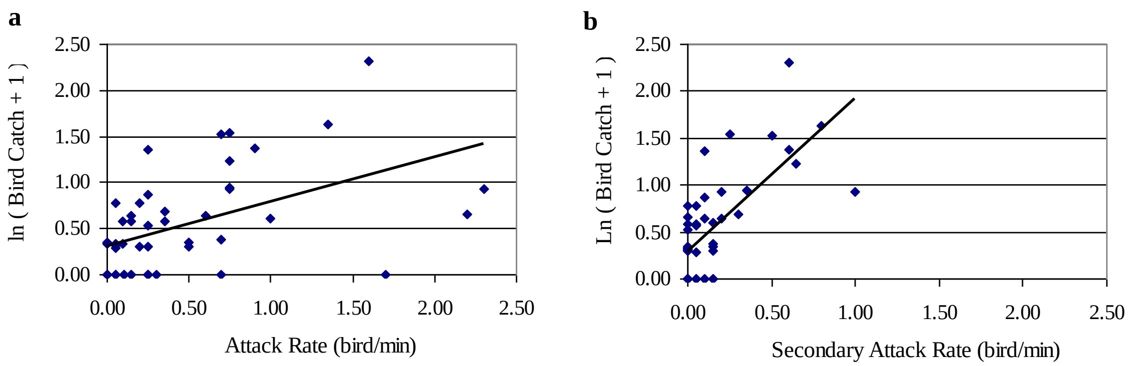


Figure 4. Regressions of seabird catch rates for primary attacks (a) and primary attacks that led to secondary attacks (b).

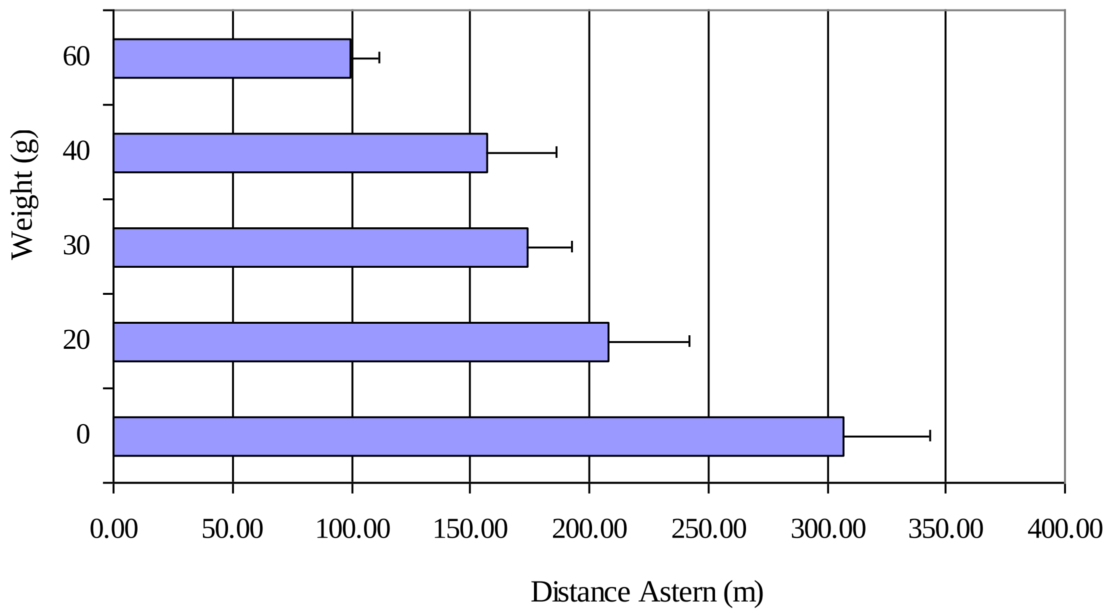


Figure 5. Estimated distance astern at which baited hooks sink to a benchmark depth of 10 m at a speed of 9.5 knots over ground. Error bars are 95% confidence intervals.