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Best practice seabird bycatch mitigation for pelagic longline fisheries targeting tuna and related species

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ABSTRACT

We comprehensively tested combinations of three primary mitigation measures in a pelagic longline fishery with one of the highest rates of interaction with what may be the world's most challenging seabird assemblage (dominated by *Procellaria* genus petrels), aboard fishing vessels typical of the Asian distant water fleet. Multiple measures were used to compare the performance of weighted vs. unweighted branch lines set with two bird-scaring lines – hybrid lines with long and short streamers – during daytime and nighttime. The weights used were a novel double-weight configuration. Secondary attacks on baits brought to the surface by white-chinned petrels drove albatross mortality. Regardless of time of day, weighted branch lines with two bird-scaring lines, deployed and maintained with an aerial extent of 100 m, reduced bird attacks by a factor of four, and secondary attacks and seabird mortality by a factor of seven, compared to unweighted branch lines, with little effect on fish catch rates and with no injuries to crew. This combination yielded zero bird mortalities when gear was set at night. We conclude that the simultaneous use of two bird-scaring lines, weighted branch lines and night setting meet our criteria for best-practice seabird bycatch mitigation for the joint-venture fleet targeting tuna and related species in the South African EEZ. To be successful, the aerial extent of bird-scaring lines should be aligned with the distance astern that baited hooks sink beyond the foraging depth of the dominant seabird – in this case white-chinned petrels to a depth near 5 m. Given that these measures were successful in one of the most challenging pelagic longline fisheries, they are likely to be widely applicable to pelagic longline fisheries using similar gear.

1. Introduction

Stemming the incidental mortality (bycatch) of non-target species in marine fisheries to maintain species diversity and ecosystem integrity is fundamental to ecosystem-based fisheries management (Crowder et al., 2008; FAO, 1995; Smith et al., 2007). Species that are highly sensitive to adult mortality, such as sea turtles, marine mammals, and seabirds, are particularly vulnerable (Croxall et al., 2012; Lewison et al., 2004). In the case of seabirds, fisheries mortality is considered the most pervasive and immediate threat to many albatross and petrel species (Croxall et al., 2012). Albatrosses are especially vulnerable, with 18 of 22 species threatened with extinction, they are the most threatened of any bird family (Phillips, 2013). Declines and poor recovery of seabird populations in the Southern Hemisphere have been repeatedly linked to mortality in longline fisheries (Gales, 1998; Tuck et al., 2001; Weimerskirch et al., 1997). The threat posed to seabirds by longline and later, other fisheries, triggered international efforts to characterize and reduce this mortality. These included The United Nations International Plan of Action for Reducing Incidental Catch of Seabirds in Longline Fisheries (FAO, 1999) and the Agreement for the Conservation of Albatrosses and Petrels, which came into force in 2004 (ACAP, 2001, 2012).

Seabird mortality occurs in longline fisheries when seabirds forage on sinking baited hooks during deployment, become hooked, and drown (Brothers, 1991; Løkkeborg, 2008, 2011). In addition to the negative consequences to bird populations, baits lost to birds increase fishing costs and reduce fish catch (Brothers et al., 1999a; Gandini and Frere, 2012; Løkkeborg, 2008, 2011; Sánchez and Belda, 2003). In some fisheries, excessive seabird mortality can lead to lost fishing opportunities due to suspensions or exclusion from a fishing area (South Africa, 2012) and, possibly, to loss of market share due to negative perceptions of fishery practices (Kirby et al., 2013). The development and implementation of best-practice seabird bycatch mitigation technologies is essential to stemming fishery-related seabird mortality and to maintaining efficient and

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sustainable fisheries (Bull, 2007; Croxall et al., 2012; Løkkeborg, 2008, 2011). We define best-practice mitigation as technologies and practices that reduce the incidental mortality of seabirds to the lowest achievable levels; are practical, safe and cost-effective; do not increase the bycatch of other taxa; and maintain or enhance the catch of target species. Experimental research comparing the performance of candidate mitigation technologies to a control of no deterrent, where possible, or to the status quo, yields definitive results; research results from tests using fishery observer data are frequently confounded (Løkkeborg, 2008, 2011; Melvin and Robertson, 2000). Carefully designed studies testing candidate best-practice mitigation technologies using multiple metrics of evaluation are key to understanding and ultimately reducing seabird mortality in marine fisheries.

Among fisheries, pelagic longline fisheries targeting tuna and billfishes and managed by international agreements (Regional Fishery Management Organizations, or RFMOs) may pose the greatest fisheries-related threat. Their wide spatial and temporal extent – over 90% of the world's oceans at all times of year – coupled with high fishing effort, high rates of seabird bycatch and minimal monitoring make them a constant risk to wide-ranging seabirds (see Melvin et al., 2013). Despite a clear and critical need, comprehensive research to develop best practice seabird bycatch mitigation technologies specific to pelagic longline fisheries is lacking (Anderson et al., 2011; Løkkeborg, 2008, 2011) creating considerable uncertainty and debate among member nations of tuna commissions regarding best-practice mitigation. In contrast, seabird bycatch mitigation is well studied and well understood for demersal longline fisheries. Experimental research established line weighting, bird-scaring lines, and night setting as accepted best practice mitigation for demersal longline fisheries, and implementation of these measures dramatically improved fishery performance (ACAP, 2013a; CCAMLR, 2011; Croxall and Nicol, 2004). Weighting longlines reduces the amount of time and the distance beyond a vessel that baited hooks take to sink below the foraging depth of seabirds. Bird-scaring lines exclude birds from the area where baits are accessible. Albatross species, and to a lesser extent petrel species, forage less and with reduced efficiency at night (Catry et al., 2004; Phalan et al., 2007; Mackley et al., 2011).

The configuration of pelagic longline gear creates unique challenges for the application of bird-scaring lines and line weighting. Surface floats used to suspend longlines from the water surface can tangle with bird-scaring lines as they are deployed, leading to problems with crew safety and crew efficiency, and in some cases, lost fishing gear (Melvin et al., 2013). Adding lead weights to the long branch lines typical of pelagic fisheries can pose serious safety issues: when a hook is suddenly released from a fish as it is landed and the weight recoils at high speed toward crew members, there is a high risk of injury (Anderson and McArdle, 2002; Boggs, 2001; Løkkeborg, 2008, 2011). Weighting branch lines may also reduce the catch rates of target fishes (Robertson et al., 2013). Fishers can be averse to setting longlines (pelagic or demersal) at night for reasons that include scheduling difficulties, safety concerns and possible effects on catch rates of some fishes.

Our comparison of the efficacy of two bird-scaring line designs in the South African tuna joint venture fishery in 2009 found that bird-scaring lines could not prevent bird attacks on unweighted branch lines. Hooks sank beyond the range of diving petrels at a distance of more than 300 m astern, three times the span of the aerial extent of bird-scaring lines (100 m; Melvin et al., 2013). Slow sinking unweighted lines caused most bird attacks, and presumably most mortalities, to occur in areas beyond the protection of two bird-scaring lines. Albatrosses attacking diving birds (white chinned petrels, *Procellaria aequinoctialis*) that had brought a baited hook to surface (secondary attacks) compounded this dynamic. Anticipating this outcome, we carried out a preliminary trial in which weighted branch lines dramatically reduced seabird mortalities compared to unweighted lines: weighted lines sank to a depth beyond the reach of white-chinned petrels within the bird-scaring line aerial extent and with no detectable effect on target fish catch day or night. Based on these results, we hypothesized that, to be effective, the aerial extent of bird-scaring lines should span the distance astern of the vessel that baited hooks were accessible to birds – a concept we referred to as 'shrink and defend'.

Here we report findings of further trials in the South African joint venture tuna fishery, comparing the performance of weighted vs. unweighted branch lines set with two bird-scaring lines during daytime and nighttime using multiple metrics. Our goals were to: (1) provide experimental evidence of the merits of combined mitigation measures, (2) shed light on the underlying mechanisms that drive seabird bycatch; (3) identify best-practice seabird bycatch mitigation measures for the South African tuna joint venture fishery, and (4) by working on vessels typical of the Asian distant water fleet and in a system with some of the highest seabird interaction rates recorded, provide recommendations for pelagic longline fisheries managed by international tuna commissions.

2. Methods

2.1. The South African tuna joint venture fishery

The Agulhas Current and the Benguela Current, which extend into the South African Exclusive Economic Zone (EEZ), are major current systems of great importance to seabirds (Croxall et al., 2012). Some 24 species of albatrosses and petrels, most of which are threatened with extinction, forage in South African waters (Petersen et al., 2009). An initial assessment of seabird bycatch in the pelagic longline fisheries targeting primarily tunas and billfishes (1998–2000) found that the South African pelagic longline fishery had one of the highest seabird bycatch rates in the world (1.6 birds/1000 hooks) killing up to 30,000 birds per year (Ryan et al., 2002). The rate was highest in the Asian fleet fishing in winter, 4.46 birds/1000 hooks. The most recent assessment, based on more complete data and assuming better compliance with bycatch mitigation measures, estimated the average bycatch rate over the eight years from 1998 to 2005 to be considerably less (0.44 birds/1000 hooks, with 1800–5900 birds killed each year) than the original estimate. Eight of the 11 confirmed species killed were threatened with extinction (Petersen et al., 2009). This analysis confirmed that the winter Asian joint venture tuna fishery had the highest bycatch rate (0.58 birds/1000 hooks). These updated bycatch rates are considerably higher than those estimated from comparable data sets of Southern Hemisphere pelagic longline fisheries (0.2–0.4 birds/1000 hooks; Bugoni et al., 2008). The South African tuna joint venture fishery met our criteria for staging research in a worst-case seabird-interaction fishery.

In 2010, foreign flagged vessels participating in the South African tuna joint venture fishery were required to fish exclusively at night (between nautical dawn and nautical dusk) and to use a single bird-scaring line of a specific design and other practices to minimize seabird mortality. If an individual permit holder exceed an annual mortality limit of 25 birds, fishing could be allowed but only with weighted branch lines (60 g within 2 m of the hook) or no fishing in the days bracketing the full moon. If bycatch exceeded 50 birds, fishing might be allowed to continue under certain conditions, including mandatory use of weighted branch lines at all times (South Africa, 2010).

2.2. Longline vessels and gear

Research was carried out aboard two Japanese longline vessels, the F/V *Fukuseki Maru No. 5* and *F/V Koei Maru No. 88*, production-fishing in the 2010 tuna joint venture fishery in the South African EEZ. Bigeye tuna (*Thunnus obesus*), yellowfin tuna (*Thunnus albacares*), albacore (*Thunnus alalunga*), and swordfish (*Xiphias gladius*) were the primary target species. The vessels and fishing operations were typical of the Asian distant-water tuna fleets that have dominated pelagic longline fishing across southern oceans (Tuck et al., 2003) and have been identified as having one of the highest impacts on seabirds (Baker et al., 2007). The research took place when seabirds are most abundant and bycatch rates are highest – the Austral winter (Petersen et al., 2009; Ryan et al., 2002; Ryan and Rose, 1995).

The fundamental unit of longline gear, the float segment, consisted of 11–12 individual branch lines clipped along 450 m of mainline suspended at depth between 0.3 m diameter surface floats. Fourteen-meter float lines, each weighted with a 220 g lead that could slide from the snap toward the float when the float line was retrieved, connected individual floats to the mainline. A line shooter delivered the mainline into the water slack – 1.4 times faster than vessel speed – allowing the mainline to form a catenary between the two floats establishing fishing depths ranging from approximately 50 to 200 m for individual baited hooks. Twenty units of gear were set between radio beacons to form a gear segment. The *Fukuseki 5* deployed 220 branch lines per gear segment and the *Koei 88* deployed 240. One set was made each day of 10–12 segments or 2000–3000 hooks on approximately 100 km of multifilament mainline. At a setting speed of 9.8 kt over ground, sets took 5–5.5 h to complete.

Unweighted branch lines were 30–35 m long and composed of varied line types and hardware. Japanese fishing masters consider branch line designs highly proprietary. Consequently, branch line design differed between the two vessels, with each using a mix of designs. In general terms, individual lines were 30–35 m long and were maintained on the vessel in coils. Unweighted branch lines typically included 4–10 m of 1.8–1.9 mm monofilament fixed to a ringed no. 4 (3.6 *sun*), Diataro-style Japanese tuna hook. Branch lines were clipped to the mainline every 7.3 s as signaled by a timer (~50 m). Baited hooks were cast into still water to port of the vessel's wake using a bait-casting machine. The machine also served to uncoil roughly 8 m of the monofilament and deliver it to the water untangled. The rest of the branch line coil was tossed by hand closer to the vessel, near the margin of the wake. Whole pilchard (*Sardinops sagax*), mackerel (*Decapterus macrallus*) and squid (*Illex* spp.) were used for bait.

2.3. Double-weight branch lines

Half of the branch lines on each vessel were weighted using the double-weight configuration developed by *Fukuseki 5* fishing master Yamazaki-san in the course of our 2009 research (Melvin et al., 2010). This novel branch line-weighting configuration consisted of a weighted section that was inserted into the monofilament section of a branch line at 2 m above the hook (Fig. 1). The weighted section consisted of 1–1.5 m length of inelastic wire or leaded line with a lead weight positioned at each end. The double-weight configuration was preferred to a single lead weight because it was more compatible with the coiled branch line system, and was considered safer. Weight spread out over 1–1.5 m was considered less prone to tangling and easier to handle in a coil than a single weight. The double-weight configuration was also less likely to injure crewmembers, as it positioned the heavier weight at 3–3.5 m from the hook – within the grasp of crew as a fish comes to the vessel. The second, lighter weight, placed 2 m from the hook, fit snugly onto the wire or line but was free to slide. This free-sliding weight, together with inelastic material inserted into the branch line, served to dampen the force of recoil should a hook suddenly come free from a fish. Initially, we used a 18–38 g configuration on 1–1.5 m of 2.7 mm diameter coated wire (total weight 85 g), but the large diameter of the coated wire and the shape of the weights caused excessive tangling. After some trial and error with the material available on the vessel over the first several days of fishing, the weighting evolved to a 12–38 g configuration, (lighter lead 2 m from the hook) using spindle-shaped lead weights on 1 m (65 g total weight, *Koei 88*) or 1.5 m (70 g total weight, *Fukuseki 5*) of a coated, monofilament lead-core line (*Kodo*).

2.4. Bird-scaring lines

Each vessel deployed two "hybrid" bird-scaring lines for the duration of every set (Fig. 2). These lines were 200 m long, with a mix of long and short streamers in their aerial extent. Lines with long streamers are typically found to be successful in demersal longline fisheries (Melvin et al., 2001, 2004), while the "light" lines favored by fishing masters in the Japanese domestic pelagic longline fleet typically have short streamers (Yokota et al., 2008).

The long streamers were single strands of UV-protected orange tubing, ranging from 8.5 m to 1.5 m, attached every 5 m in the first aerial 50 m. Branched 2-m strips of greenish-yellow packing-strap material were tied into the line between each long streamer. One-meter strips of the same material were tied in at the midpoint of the strip every meter throughout the latter half of the aerial extent (51–100 m), closest to the water. The in-water section of the line also had 1-m strips of packing strap material clustered in threes every 5 m from 101 m to 150 m and every 10 m from 151 m to 200 m. This bottlebrush-like arrangement generated enough drag to create a 100 m aerial extent when the vessel maintained 9.8 kt. This innovation was also developed by fishing master Yamazaki-san as an alternative to towed objects or devices, which tangle frequently on surface floats (Melvin et al., 2013). The scaring lines were attached to dedicated davits (tori poles) on the upper deck to port and starboard of the stern. The attachment point of the port scaring line was positioned 5 m outboard on the *Fukuseki 5* and 4 m outboard on the *Koei 88*. The *Koei 88* pulled its starboard scaring line to port via a lazy line, typically positioning it midway between the starboard side and the midpoint of the stern. The *Fukuseki 5* did not.

2.5. Experimental design

A typical set began at 03:00 hours, with at least three gear segments set in daylight hours, and ended by 08:00. Half of each vessel's branch lines were weighted and the other half left unweighted. Both types were deployed on both vessels in each set. At night, weighted and unweighted gear segments alternated. In the daylight period, the crew set 3–5 segments of purely weighted or unweighted lines. To reduce bias due to environmental factors, vessels deployed opposite weighting configurations in any given day and alternated configurations day to day. Vessels coordinated fishing operations and set gear at the same time, in the same direction, and typically within sight of each other. Longline retrieval began 3 h after the set was completed, typically at about 11:00 hours. Given that the last hook set was the first one hauled, hooks set at night fished for at least 12 h spanning both day and night, while hooks deployed during daylight hours fished fewer than 3–6 h and exclusively during the early part of the day.

2.6. Data collection

Fishery researchers collected data on seabird attacks on baited hooks and seabird numbers during the daylight portion of each set.

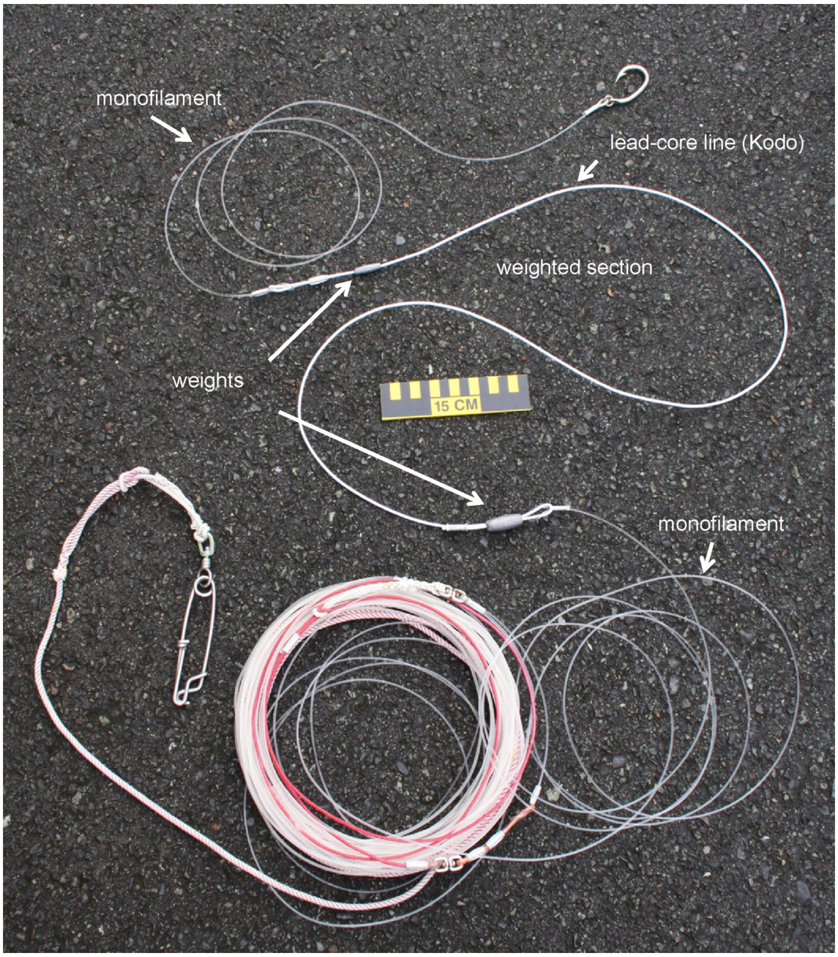

Fig. 1. Double-weight branch line. A weighted section, made up of a 1–1.5 m length of inelastic wire or leaded line with a lead weight positioned at each end, was inserted into the monofilament section of the branch line 2 m above the hook (see text).

Primary and secondary attacks were monitored during the setting of one gear segment (25–30 min). A primary attack was an unambiguous attempt by an individual bird to take bait from a hook – typically a dive, lunge, or plunge directly over a sinking hook. A secondary attack was another bird or a group of birds attempting to steal bait from a bird that had successfully brought it to the surface after completing a successful primary attack. Both were recorded as occurring in one of 21 locations delineated by seven areas astern (0–25 m, 26–50 m, 51–75 m, 76–100 m, 101–125 m, 126–150 m, and 151–200 m astern) and by three lateral areas (within the two scaring lines, to port of the port line or to starboard of the starboard scaring line). Markers inserted into the scaring lines served as reference points to judge distance astern.

Data were recorded on the physical environment and vessel operations immediately prior to the attack rate observation period. These data included area (South or East Coast, Fig. 3), barometric

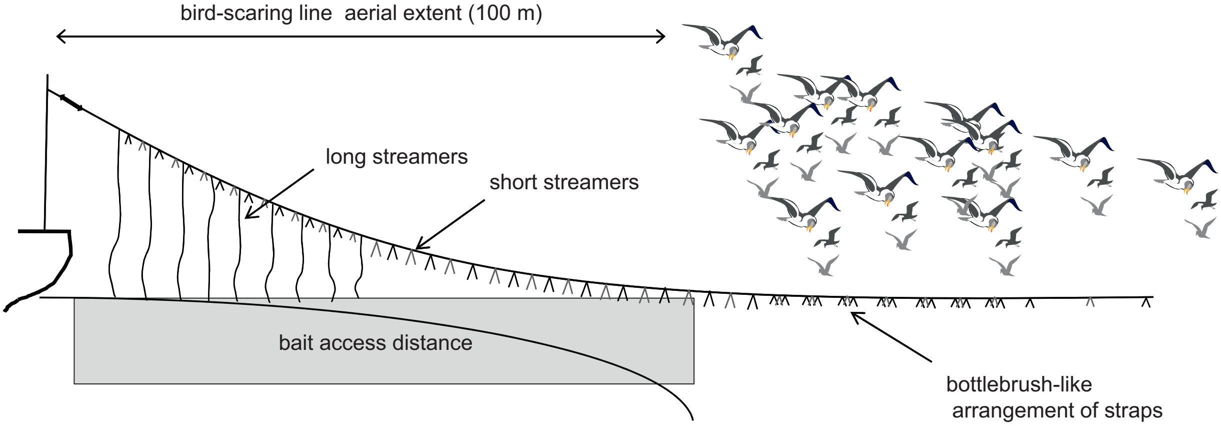

Fig. 2. Hybrid bird-scaring line with long streamers along the first 50 m of the aerial extent and short streamers along the 51–100 m span of the aerial extent (see text). Bait access distances is the distance astern the baited hooks sink beyond the hypothetical foraging depth of white-chinned petrels.

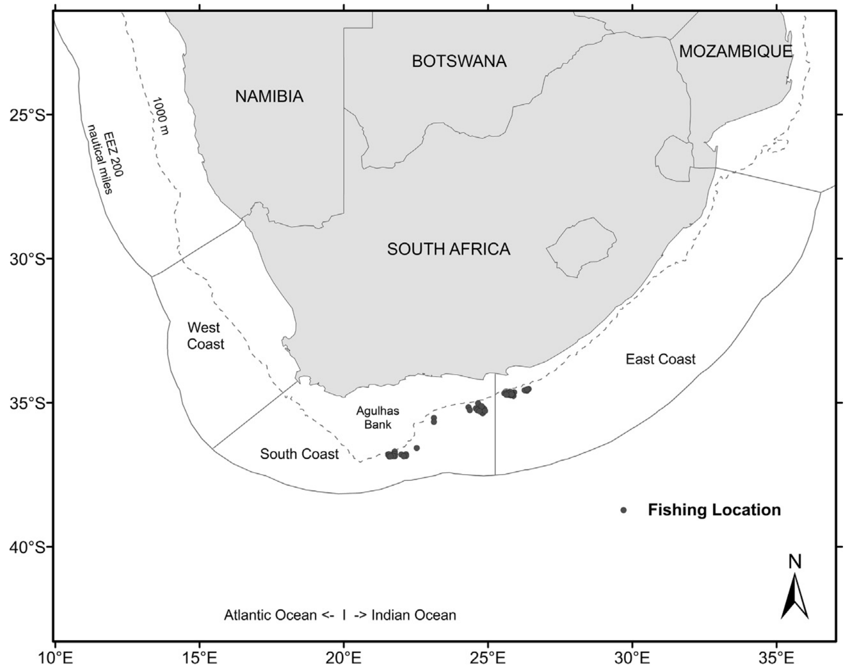

Fig. 3. Map of the South African Exclusive Economic Zone showing the locations of longline sets during 2010 experimental seabird bycatch mitigation trials in the joint venture tuna fishery. Area boundaries are as per Ryan et al. (2002).

pressure, Beaufort sea state, distance from the shelf break, percent cloud cover, depth, latitude and longitude, maximum visibility, moon phase, sea temperature, set duration, streamer line aerial extent, swell height, total hooks, vessel speed, and wind speed and direction (see Melvin et al., 2013). The landing location of baited hooks and coils relative to the wake and port bird-scaring line was recorded for 10 sequential bait throws prior to attack rate observations. Immediately following the attack rate observation, researchers recorded the number of seabirds (on the water and in the air) by species in a 250 m hemisphere centered at the midpoint of the stern, together with data on the performance of the bird-scaring lines (aerial extent).

Two researchers on the *Fukuseki 5* observed the retrieval of all hooks during each haul. The single researcher on the *Koei 88* observed five to six of the 11–12 gear segments set with priority given to observing the retrieval of all hooks deployed during the dawn–daylight period. Catches of all taxa were recorded at the species level by gear segment. A count was made of seabirds attending the vessel midway through a hauling period using the same protocol as for the set. The bridge crew independently recorded the numbers of fishes and birds caught per gear segment in the ship's logbook for the entire haul. Researchers routinely crosschecked their catch data with those in the logbook to confirm the accuracy of crew-collected data. When researchers observed that weighted branch lines might be tangling more often than unweighted lines, they began recording the numbers of tangled branch lines in one float segment (11 or 12 hooks) per radio beacon segment. Anything other than a completely knotless branch line was considered a tangle. Most were overhand knots occurring where hardware joined different branch line materials at locations other than the hook. As we could not determine at what point tangles occurred, we assumed that all the baited hooks remained available to seabirds and fishes.

Hook sink rates were measured with Wildlife Computer MK9 and Star Oddi DST Centi-ex time-depth recorders (TDRs). The water entry time was recorded for each TDR to the nearest second using a digital wristwatch. Seconds to 2, 5, and 10 m depths were extracted from each data record and corrected to compensate for the weight of the TDR, and in the case of Star-Oddis, also for the effect of the protective housing, using the results of static sink rate tests. How far astern baited hooks reached various depths was estimated by multiplying mean seconds to depth by vessel speed over water (5.04 m/s).

2.7. Data analyses

We analyzed data from sets for which bird-scaring lines did not foul, when the aerial extent of bird-scaring line was >80 m, and for gear segments with purely weighted or unweighted branch lines. We set out to find the best models to describe: (1) counts of bird attacks throughout the area monitored (200 m astern), (2) counts of dive bird attacks beyond 100 m, (3) counts of birds caught, and (4) counts of fish caught. All models were generalized linear models with a log-link and the offset equal to the number of hooks for the gear segment. A Poisson error term is an appropriate model for count data where the mean and variance are equal. For models exhibiting overdispersion (i.e., variance exceeding the mean), an observation level random effect (OLRE) was used for mixed models and a dispersion factor empirically estimated from the data for fixed effects models using the quasi-Poisson Likelihood (Zuur et al., 2009). Generalized linear mixed models were used to model bird attacks (within 200 m astern), bird catch, and fish catch. A fixed-factor generalized linear model was used to find the best predictors of the daily variation in bird attacks beyond 100 m.

Model selection to find the optimal mixed model proceeded as follows: (1) we fitted a saturated fixed-effects model with all main effects and two-way interactions; (2) identified the optimal random effects for the saturated model; and finally, (3) we selected the optimal fixed factors given the chosen random effects from Step 2 (Bolker et al., 2008; Zuur et al., 2009). At each step, the "best-fitting" model was selected using the AICc, the Akaike Information Criterion (AIC) adjusted for sample size (Burnham and Anderson, 2002).

The model selection approach for the optimal fixed effects utilized the *glmulti* function in the *glmulti* package (Calcagno, 2011) in R, which runs an exhaustive search for all possible models and retains the best models with the lowest information criteria (AICc).

The *glmulti* function allowed us to interpret the importance of, or relative evidence for, how each of the factors correlated with the response variable, thus providing the means to identify factors that never contributed to the best models, those that frequently contributed to the best models, and those that were confounded with other factors. Calculations were done via the *glmer* function from the lme4 package (Bates et al., 2011), and the *glmulti* package (Calcagno, 2011) in R (R Development Core Team, 2011).

2.7.1. *Attack rate models*

Because attacks by surface birds were few and occurred only on unweighted lines on just two of 62 days, we included only diving birds in our models of attack rates. One extreme observation, 48 attacks beyond 100 m, was nearly triple the next highest value, 17 attacks. To avoid compromising the accuracy of our models and interpretation for the rest of the data, we excluded all the observations recorded on this day (0 attacks within 100 m and 48 attacks beyond 100 m). We evaluated whether these observations were consistent with the trends shown by the remaining data by using our final models to predict observations for the excluded day. In the mixed model for bird attacks within 200 m astern, models were similar: the large variance in the extreme observation was captured by the random intercept. In the fixed-effects model for bird attacks beyond 100 m astern, model results were very different: covariates associated with this extreme observation did not explain this level of attacks. This assessment confirmed that the 48 attacks observed beyond 100 m recorded were anomalous and should not be included in our models. The final modeling data set was comprised of 61 observations of weighted (30) and unweighted (31) lines.

2.7.2. *Model for bird attacks within 200 m astern*

For seabird attacks by diving birds throughout the entire area monitored (200 m astern), candidate fixed factors were *weight* (weighted vs. unweighted lines) and *distance astern* (within or beyond 100 m), which were the fixed factors of primary interest, plus *vessel* (A vs. B), a nuisance fixed factor. The number of hooks per gear segment was the offset. The random factors considered for these models included a *day* random effect (the sequence of a given day within the trip), and an observation-level random effect (OLRE) associated with each gear segment to account for any overdispersion in the mixed model (Breslow, 1990).

2.7.3. *Model for bird attacks beyond 100 m astern*

Because the *distance astern* factor in the first bird attack model was highly significant and very few attacks occurred within 100 m, a second attack model was constructed to explore which fixed factors were most associated with diver attacks beyond 100 m. Five fixed factors were included: *weight, vessel*, percentage of branch line *coils* tossed into the wake, *vessel speed*, and the abundance of diving birds during the set (*abundance*). All two-way interactions between these factors were also included. The number of hooks per gear segment served as the offset.

2.7.4. *Model for bird catch*

The bird-catch analysis was constrained to bird catch by gear segments deployed during daylight hours to align with the hours that bird attacks and abundances were collected. In addition, nearly all (89%) of bird mortality occurred during the day. Vessels deployed a mean of 4.2 gear segments per day during daylight hours yielding a total of 261 segments (261/727 = 36% of total gear segments). For modeling, catch data per gear segment were aggregated by weighting treatment (weighted vs. unweighted) within each day (set) by vessel (30 observations for weighted lines, and 32 for unweighted lines). Attack rates and bird abundance for the gear segment sampled in a given day were assumed to be representative of all gear segments deployed after dawn on that day. Although the main covariate of interest was *weight*, four additional covariates were included in the bird catch models: *vessel*, the rate of *primary attacks*, rate of *secondary attacks*, and bird *abundance* during line setting. The random factors considered for this model included a *day* random effect (the sequence of a given day within the trip), and an observation-level random effect (OLRE) associated with each gear segment to account for any overdispersion in the mixed model (Breslow, 1990).

Table 1

Summary statistics of metrics to evaluate the effect of unweighted and weighted branch lines and night vs. day setting on seabirds and target fishes. All sets were made with two hybrid bird-scaring lines deployed – one to each side of sinking baited hooks and each with an aerial extent of 100 m. Data are derived from 62 research gear deployments (sets) or a total of 169,279 hooks.

Metric	Unweighted branch lines		Weighted branch lines	
Total hooks	78,588		90,691	
Observed hooks	7218		6768	
Bird attacks (primary)	290		66	
Birds caught	23		4	
Day	20		4	
Night	3		0	
	Mean	SE	Mean	SE
Bird attacks				
Primary rate (/1000 hooks)	40.6	7.04	9.81	2.81
% Secondary	57.6	–	33.3	–
Bird fatalities/1000 hooks	0.283	0.063	0.042	0.021
Day	0.633	0.148	0.124	0.062
Night	0.064	0.037	0.000	0.000
Total target fish/1000 hooks	14.05	0.765	13.2	0.668
Sink rate (m/s to 10 m)	0.192	1.716	0.263	1.160
Distance to 10 m depth (m)	262.9	8.653	192	5.847
Tangles/1000 hooks	56	0.006	198	0.009

2.7.5. *Model for fish catch*

Data for this model were total target fish catch per gear segment (727 gear segments over 62 fishing days), with the number of hooks per gear segment as the offset. Target fish catch (the sum of bigeye, yellowfin and albacore tunas and billfishes) was modeled using four fixed factors: *weight* (the primary factor of interest), *vessel*, post- and pre-nautical dawn (*day–night*), and *c-hooks*. The c-hooks variable was the cumulative number of hooks set preceding an individual gear segment in a given day, thus providing an inverse measure of soak time. The random factors considered for this model included a *day* random effect (the sequence of a given day within the trip), and an observation-level random effect (OLRE) associated with each gear segment to account for any overdispersion in the mixed model (Breslow, 1990).

In all models, the significance of the coefficients and confidence intervals for the effect sizes in the final mixed models were estimated using bootstrapping methods; models with only fixed effects used *t*-statistics that were adjusted for over- or under-dispersion by multiplying the estimated standard error by the dispersion estimate. We used Welch's *t*-test, which assumes unequal variance, to compare the seconds to benchmark depths between weighted and unweighted branch lines within vessels and overall.

3. Results

Research sets were made 28 July through 30 August 2010. Daylight observations were successfully carried out during 62 research sets, 31 sets (16 unweighted/15 weighted) on the *Fukuseki 5* and 31 (16 unweighted/15 weighted) on the *Koei 88*, yielding a total of 169 279 hooks deployed (Table 1). Vessels fished in two general locations: South Coast (56% effort) and East Coast (44% effort; Fig. 3). Extreme weather precluded two days of daylight

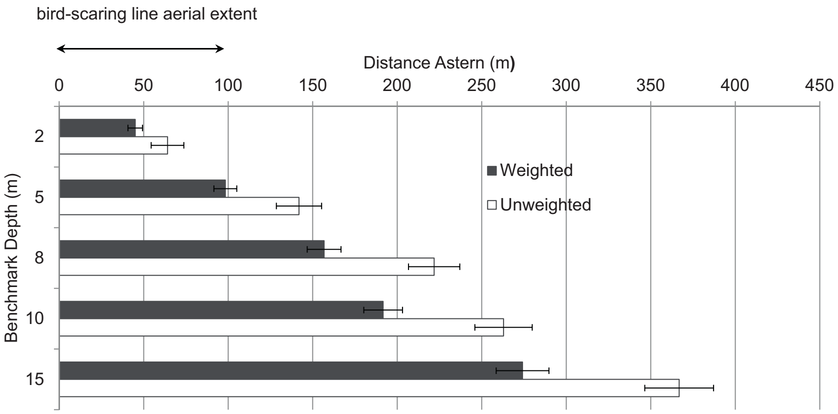

Fig. 4. Distance astern at which baited hooks sink to 2 m, 5 m, 8 m, 10 m and 15 m for unweighted and weighted branch lines. Distances were estimated as the product of vessel speed (5.042 m/s or 9.8 kt) and seconds to each specified depth. Error bars are 95% confidence intervals.

observations on both vessels. In general, weather was relatively mild during the study period, wind speed averaged 13.4 kt (range 0–33 kt), and swell height averaged 2.2 m (range 1–5 m). Mean aerial extent of bird-scaring lines was 100 m on both vessels. Bird-scaring lines tangled on surface floats during daylight observations in 3 out of 62 research sets.

3.1. *Overall trends in seabird behavior*

More bird species attended the haul (20 species) than the set (17 species, Table 2). Of these, eight species were classified as threatened with extinction and 11 were ACAP listed species (ACAP, 2013b). White-chinned petrels were by far the most abundant, averaging nearly 40 birds per set or haul observation. Yellow-nosed-type albatross (*Thalassarche chlororhynchos/carteri*), Cape petrels (*Daption capense*) and black-browed albatross (*T. melonophrys*) were the most abundant surface-foraging birds.

Only four of the 17 species attending the set made primary attacks on baits and were killed: white-chinned petrels, yellow-nosed-type and black-browed albatrosses, and cape gannets (*Morus capensis*, Table 2). Diving seabirds made the most primary attacks (98%) and albatrosses the fewest (2%). Of the diving seabirds, white-chinned petrels made the great majority of attacks (96%) yielding the highest attack rate (24.2 attacks/1000 hooks). Cape gannets attended few sets (21%) but made 4% of attacks at a mean rate of 1.1 attacks/1000 hooks. Albatross attack rates (0 to 0.3 attacks/1000 hooks) were near two orders of magnitude lower than that of white-chinned petrels. Among the albatrosses, yellow-nosed-type albatross attacked most, making 1% of all primary attacks, while black-browed albatrosses accounted for 0.6%. More than half (53.1%) of all primary attacks (356) led to secondary attacks. Although recording the species making secondary attacks was not part of our protocol, researchers reported that almost all the secondary attacks involved albatrosses and large petrels.

A total of 27 bird mortalities occurred during 62 sets (Table 2). White-chinned petrels were killed at the highest rate (0.106 birds/1000 hooks). Diving birds accounted for most mortality (70%) while albatrosses accounted for the remainder. Although shy-type albatross (*T. cauta/steadi*) were relatively abundant (mean = 2.8 birds/set) and attended 68% of sets, only three were killed; no shy-type albatross primary attacks were observed throughout the study.

3.2. *Sink rates: weighted vs. unweighted branch lines*

Overall, weighted branch lines sank considerably faster than unweighted lines to all benchmark depths: 3.8 s, 8.6 s and 14.1 s sooner to 2, 5 and 10 m depths, respectively (Table 3). Sink rate differences translated into baited hooks on weighted lines reaching a depth at 10 m while 71 m closer to the vessel than hooks on unweighted lines (192 vs. 263 m, respectively). Both branch lines sank to our benchmark 10 m depth considerably beyond the 100 m aerial extent of the bird-scaring lines (Fig. 4). No crew injuries occurred during the study, which suggests that both branch line types were safe. However, weighted branch lines tangled on themselves 3.5 times more often than did unweighted lines (Table 1), but with no obvious effect on fish catch.

3.3. *Seabird attack rates: weighted vs. unweighted branch lines*

Overall, the rate of bird attacks on baited hooks was more than four times higher on unweighted than on weighted lines (40.6 attacks/1000 hooks vs. 9.8 attacks/1000 hooks, Table 1 and Fig. 5). The six albatross primary attacks recorded were all on unweighted lines between 100 and 150 m astern of the vessel and to port of the port bird-scaring line. Only 3.7% of bait attacks by diving birds were within the mean aerial extent of the hybrid bird-scaring lines (100 m) regardless of branch line type (Figs. 4 and 5). Beyond 100 m, however, divers attacked unweighted lines two to four times as often as they did weighted lines (Fig. 5). For both branch line types, attacks peaked from 126 m to 150 m beyond the 150 m mark. Attacks dropped sharply beyond 150 m on weighted but not on unweighted lines. Attack rates did not peak for either line immediately beyond the 100 m bird-scaring line aerial extent,

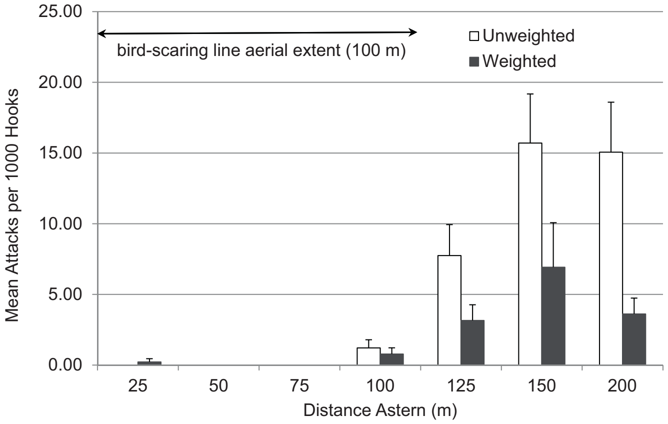

Fig. 5. Distribution of primary attacks (attacks per 1000 hooks) of diving seabirds birds on baited hooks for weighted and unweighted branch lines by distance astern (m).

Table 2
Mean seabird attendance and standard error (SE) during the haul and during the set (birds), proportion of sets present (set occurrence), attack rate (attacks per 1000 hooks) and total mortalities (birds). S, surface foragers; D, diving foragers. Data are from daylight observations of 62 research sets made by two fishing vessels from July 28 to August 30 2010.

Species	Scientific name	Surface or diving guild	Number of birds per haul		Number of birds per set		Set occurrence	Attacks per 1000 hooks		Observed mortalities
			Mean	SE	Mean	SE		Mean	SE	*n*
White-chinned petrel	*Procellaria aequinoctialis*	D	40.63	3.30	38.61	2.91	1.00	24.2	4.1	18
Yellow-nosed albatross	*Thalassarche chlorohynchos/carteri*	S	32.59	3.53	9.32	1.50	0.95	0.3	0.2	4
Cape petrel	*Daption capense*	S	22.76	2.56	6.02	1.58	0.79			
Black-browed albatross	*Thalassarche melanophrys*	S	11.54	1.59	2.00	0.30	0.53	0.1	0.1	1
Shy albatross	*Thalassarche cauta/steadi*	S	4.83	0.56	1.89	0.24	0.68			3
Wilson's storm petrel	*Oceanites oceanicus*	S	3.37	0.65	0.50	0.17	0.16			
Cape gannet	*Morus capensis*	D	3.20	1.27	0.29	0.09	0.21	1.1	0.8	1
Antarctic skua	*Stercorarius antarctica*	S	1.99	0.47	0.16	0.05	0.15			
Southern giant petrel	*Macronectes giganteus*	S	0.63	0.17	0.02	0.02	0.02			
Giant petrel	*Macronectes* sp.	S	0.49	0.17	0.21	0.06	0.19			
Sooty shearwater	*Puffinus griseus*	D	0.32	0.08	0.10	0.04	0.10			
Great-winged petrel	*Pterodroma macroptera*	S	0.29	0.08	0.11	0.05	0.10			
Northern giant petrel	*Macronectes halli*	D	0.24	0.07						
Soft-plumaged petrel	*Pterodroma mollis*	S	0.22	0.08	0.16	0.07	0.11			
Wandering albatross	*Diomedea exulans*	S	0.22	0.07	0.02	0.02	0.02			
Northern royal albatross	*Diomedea sanfordi*	S	0.15	0.05	0.11	0.05	0.10			
Southern royal albatross	*Diomedea epomophora*	S	0.10	0.05	0.03	0.02	0.03			
Antarctic prion	*Pachyptila desolata*	S	0.08	0.06						
Arctic tern	*Sterna paradisaea*	S	0.02	0.02	0.11	0.06	0.06			
Gray petrel	*Procellaria cinerea*	D	0.02	0.02						

Table 3
Mean seconds to benchmark depths of baited hooks on unweighted and weighted branch lines. Statistical comparisons are the results of Welch's *t*-test.

Depth	*n*	2 m				5 m				10 m			
Branch line		Mean (s)	SE	*t*	*p*	Mean (s)	SE	*t*	*p*	Mean (s)	SE	*t*	*p*
Unweighted	49	12.7	0.98	3.53	0.001	28.1	1.35			52.1	1.72		
Weighted	54	8.93	0.44			19.5	0.69	5.70	0.000	38.0	1.16	6.82	0.000

indicating that the bird-scaring lines provided some deterrence for an additional 25 m beyond the aerial extent. No bird attacks occurred between the two bird-scaring lines throughout their 100 m aerial extent – the area from which we intended to exclude birds (Fig. 6). Importantly, more primary attacks resulted in secondary attacks on unweighted lines (57.6%) than on weighted lines (33.3%, Table 1).

3.3.1. *Model of bird attacks within 200 m astern*

The model of diver attacks within 200 m astern of the vessel with all three fixed factors (*weight*, *vessel*, and *distance astern*), plus all two-way interactions, yielded a dispersion estimate of 2.5, signaling the need to introduce the *observation* level random effect (OLRE) to model the overdispersion. The AICc values for the sequentially fit models are shown in Supplementary Materials Table 4.

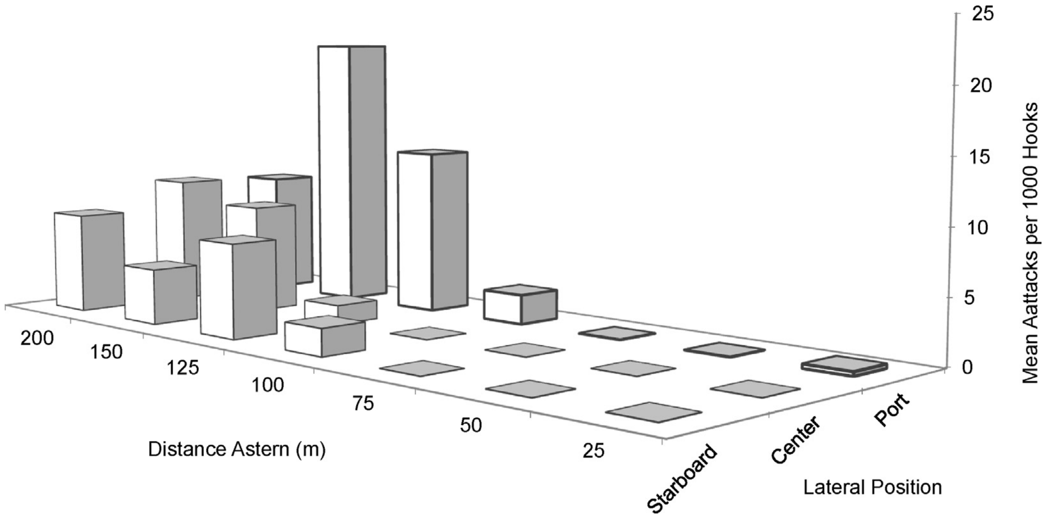

Fig. 6. Distribution of primary attacks (attacks per 1000 hooks) by diving seabirds by distance astern and lateral position relative to bird-scaring lines for weighted and unweighted branch lines combined. Center, between bird-scaring lines (BSL); port, to port of the port BSL; starboard, to starboard of the starboard BSL. Only 6 attacks occurred by surface foraging birds and all were to port beyond 75 m (see text). Error bars are 95% confidence intervals.

The model incorporating both random effects (*observation* and *day*) proved a better fit than a model with only *observation* as a random effect (AICc = 193.9 and 195.7, respectively, and the reduction in deviance was 4.1, significant with a Chi-square test with 1 df, $p < 0.05$). The mixed model using *weight* and *distance astern* plus their interaction term yielded the best fit (AICc = 189.4). However, consideration of the bootstrapped 95% confidence intervals indicated that the interaction term was not significant ($p = 0.26$). Dropping the interaction term yielded an AICc change of only 0.4, and the increase in deviance was 2.6, not a significant change with a Chi-square test with 1 df ($p > 0.05$). Thus, the final mixed-effects model yielded *weight* and *distance astern* as main fixed effects, and random intercepts for *observation* and *day* (Supplementary Materials Table 5). The final model explained 73% of the total model deviance.

3.3.2. Model of bird attacks beyond 100 m astern

The best, fixed effects model of diver attacks beyond 100 m included various combinations of *weight*, vessel *speed*, abundance of diving birds during the set (*abundance*), *vessel*, and the interaction between *weight* and *abundance*. The covariates *weight* and *abundance* and their interaction term were present in each of the top three models (Supplementary Materials Table 4). The addition of vessel *speed* significantly contributed to the reduction in AICc (16.6 units better than the next best-fit model, Supplementary Materials Table 4). The final model with *weight*, *abundance*, vessel *speed*, and the interaction between *weight* and *abundance* explained 60% of the total model deviance. Diving-bird *abundance* during the set was not statistically significant as a main effect ($p > 0.05$), but it did contribute to a significant interaction term with *weight* ($p < 0.001$, Supplementary Materials Table 6).

3.4. Seabird mortality: weighted vs. unweighted branch lines

Weighted branch lines combined with hybrid bird-scaring lines dramatically reduced seabird mortality with little effect on total fish catch. Only 4 of 27 bird fatalities (two white-chinned petrels, one shy albatross, and one cape gannet) were on weighted branch lines – representing a more than six-fold decrease in mean seabird bycatch rate compared to unweighted lines (0.042 birds vs. 0.283 birds/1000 hooks, Table 1).

3.4.1. Model of bird catch

The saturated fixed-effects model with five factors and all two-way interactions had a dispersion estimate of 0.98, indicating that the Poisson errors were a reasonable fit. The estimated variances for the *day* and *observation* random effects were zero, indicating that these random intercepts were not needed. Consequently, the *glmulti* function identified the top fixed-effects models with no restriction on factors and with primary and secondary attacks explicitly included or excluded (Supplementary Materials Table 4). A model with *secondary attacks*, *abundance*, and the interaction between *secondary attacks* and *vessel* as fixed effects emerged as the best fixed-effects model of bird bycatch rates (df = 4, AICc = 75.9, deviance explained = 50%, Model A, Supplementary Materials Table 7A). *Secondary attacks* remained as an independent fixed factor in all best-fit models unless it was explicitly excluded, including when *primary attacks* and *weight* were forced into models (Supplementary Materials Table 4). *Primary attacks* emerged as an independent factor only when *secondary attacks* was excluded (df = 5, AICc = 82.7, deviance explained = 44%). Excluding both *secondary* and *primary attacks* from the model was the only situation where *weight* emerged as a significant independent factor; however, the fit and deviance explained were considerably worse than other models that included attacks (df = 4, AICc = 91.4, deviance explained = 27%, Model B, Supplementary Materials Table 7B). These results strongly suggest that secondary attacks are the primary driver of bird mortality. Attacks are also significantly affected by the weighting of the branch lines; therefore *attack rates* (secondary and primary) functioned as proxies for *weight*.

3.5. Seabird mortality: nighttime vs. daytime

Regardless of line weighting, the rate of seabird mortality was more than 13 times higher during daylight hours (0.378 birds/1000 hooks) than nighttime (0.028 birds/1000 hooks). Twenty-four fatalities occurred in day and three at night. All birds caught at night were white-chinned petrels; one was caught in the nights bracketing the full moon.

3.6. Target fish catch: weighted vs. unweighted branch lines

Overall, mean target catch of tunas and billfishes was nearly equal on the two branch line types (14.1 fish/1000 hooks on unweighted and 13.2 fish/1000 hooks on weighted branch lines; Table 1).

3.6.1. Model of fish catch

The saturated fixed-effects model had a dispersion estimate of 3.0, indicating the need for the OLRE to model the overdispersion. Sequential AICc values (Supplementary Materials Table 4) and non-zero variances for the random intercepts indicated the need for both the *observation* (an OLRE) and *day* random intercepts to adequately capture the variability in the target fish catch data. The resultant model included the two random intercepts plus *day–night* and *c-hooks* and their interaction as fixed effects (df = 6, AICc = 1536, Supplementary Materials Table 4); all factors were significant ($p < 0.05$). When we added *weight* to the optimal model, the fit was nearly identical (delta AICc = 0.5, Supplementary Materials Table 4), with very little change to the coefficients; *weight* was the only non-significant factor ($p = 0.15$, Supplementary Materials Table 8). These results suggest that *c-hooks* and *day–night* are important factors, and that the persistent significance of the interaction term shows that they are highly correlated or confounded with each other (night-sets had fewer c-hooks and all day-sets had more). Our modeling suggests that weighting branch lines did not have a strong influence on fish catch and that fish catch rates may be confounded with other factors.

3.7. Target catch: nighttime vs. daytime

Due to the confounding nature of *day–night* and soak time (*c-hooks*), we modeled night and day separately to tease apart these effects on fish catch. In the nighttime model, the inclusion of the *day* random effect significantly improved the fit over the model with just the "observation" random effect (delta AICc = 977–1081 = −104, Supplementary Materials Table 4; Chi-square = 106.41 on 1 df, $p < 0.001$). With the random effects established, a model with *vessel* and *c-hooks* emerged as the best-fit model based on the AICc (df = 5, AICc = 971.5), but the improvement in AICc was minor relative to the saturated mixed model (delta AICc = 971.5–977 = −5.5) and fixed factors were not statistically significant ($p > 0.05$). Forcing *weight* into the model had little effect on fit (delta AICc = 973.6–971.5 = 2.1, Supplementary Materials Table 4) or structure – there was very little change in the estimated values of the covariates and again, none were statistically significant ($p > 0.05$, Supplementary Materials Table 9 and Fig. 7A). Ultimately, a model with random but no fixed factors differed from the optimal mixed-effects model by only one AICc unit (df = 3, AICc = 972.5 vs. df = 5, AICc = 971.5). This suggests that all fixed covariates, including *weight*, were not strong predictors of fish catch at night, and most of the variability was random.

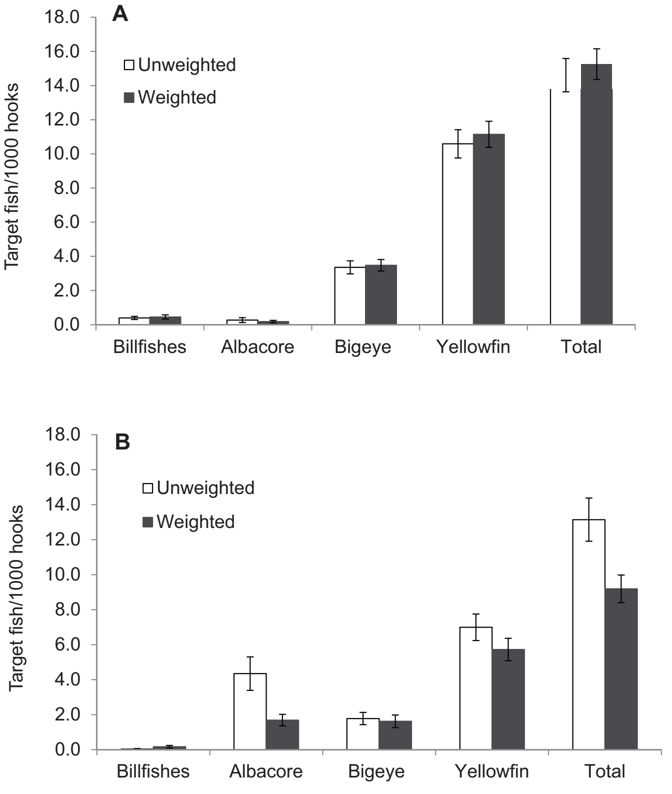

Fig. 7. Catch rate (per 1000 hooks) of target fishes (tunas and billfishes) for weighted and unweighted branch lines for night (pre nautical dawn, A) and day (daytime, B). Error bars are standard errors.

In the daytime fish catch model, including both random effects again significantly improved the model fit (delta AICc = 497–515 = −28, Supplementary Materials Table 4; Chi-square = 30.03, $p < 0.001$). With the two random effects established, an optimal mixed-effects model had a slightly better fit than the saturated model (delta AICc = 493.2–497.1 = −3.9). Covariates included *vessel*, *c-hooks*, their interaction, and the interaction between *weight* and *c-hooks*. Only *c-hooks* and its interaction with *weight* were statistically significant ($p < 0.05$). Forcing the covariate *weight* into the model yielded a comparable model fit (AICc only 0.6 units larger than the optimal model), with *weight* and *c-hooks* statistically significant covariates ($p < 0.05$, Supplementary Materials Table 10). Negative coefficients indicate weighted branch lines had a lower target-fish catch during the daytime, and that fish catch rates were positively correlated with hook soak time. However, longer daytime soaks may be confounded with the effect of increasing light levels. The apparent negative influence of the weighted branch lines on fish catch during daytime setting varied by species, with albacore and yellowfin tuna most affected (Fig. 7B).

4. Discussion

4.1. Seabird assemblage

We found white-chinned petrels were the dominant seabird species in the South Africa EEZ in the Austral winter: they were most abundant, made the most attacks, precipitated secondary attacks by albatrosses, and were most killed. These findings match our 2009 finding (Melvin et al., 2013) and that of a multi-year analysis of seabird mortality in the South African tuna joint venture fishery (Petersen et al., 2009). Also common to these studies was the finding that the four common *Thalassarche* spp. were the most frequently killed surface foraging-seabirds.

4.2. Weighted vs. unweighted branch lines

With two bird-scaring lines deployed as a constant, branch lines weighted using the novel double-weight configuration outperformed unweighted branch lines by all metrics of comparison. Regardless of time of day, weighted branch lines with two bird-scaring lines, deployed and maintained with an aerial extent of 100 m, reduced bird attacks by a factor of four (9.8 vs. 40.6 attacks/1000 hooks), secondary attack rates (3.26 vs. 23.47 attacks/1000 hooks) and seabird mortality rates (0.042 vs. 0.283 birds/1000 hooks) by a factor of seven compared to unweighted branch lines, with little effect on fish catch rates (13.2 vs. 14.05 birds/1000 hooks weighted and unweighted, respectively), and no injuries to crew. Combined with a third mitigation measure, nighttime setting, weighted branch lines and two bird-scaring lines yielded zero bird fatalities (vs. 0.064 birds/1000 hooks for unweighted lines set during the day). During daylight hours weighted lines plus two bird-scaring lines outperformed unweighted lines by a factor of five (0.124 vs. 0.633 birds/1000 hooks). Our finding that the factor “weight” was highly significant (with a negative coefficient) in all attack rate catch rate models underscores the strong influence of branch line weighting on reducing seabird mortality in this fishery.

These results conform to results of pilot-scale comparison of our unweighted and weighted branch lines in 2009. In that comparison, weighted lines (single 60 g lead weight positioned 1 m from the hook) in combination with two bird-scaring lines (a hybrid or short streamer design), yielded an 18-fold reduction in the rate of seabird mortality compared to unweighted branch lines, with no detectable difference in fish catch rates (Melvin et al., 2013). Although branch line weighting configuration differed, seabird bycatch rates on weighted lines were similar between years (0.060 birds/1000 hooks and 0.042 birds/1000 hooks, for 2009 and this study, respectively). Unlike previous studies of branch line weighting in pelagic fisheries, which focused solely on contrasting sink rates among various weighting configurations (Anderson and McArdle, 2002; Hu et al., 2005; Robertson et al., 2010), this study conclusively shows that a specific branch line weighting configuration successfully and safely reduces seabird interactions with no effect on fish catch rates.

In an era in which combinations of seabird bycatch reduction technologies are increasingly required (see below), research focused on optimizing branch line weighting in the context of combined mitigation measures will best serve fisheries management. As an example, we found that no seabirds – albatrosses or divers – were observed attacking baited hooks between two hybrid bird-scaring lines on unweighted or weighted branch lines out to 100 m (5 m depth) in daylight. This suggests that sink speeds in the upper 0–2 m may be less important than previously thought (Robertson et al., 2010) when branch line weighting is combined with two bird-scaring lines that are properly deployed. Quick sinking of baited hooks is central to successful seabird bycatch mitigation in all longline fisheries; however, the weight and configuration of weighted branch lines to protect seabirds should, where circumstances allow, be based on multiple metrics of seabird interactions, fish catch rates, hook sink rates, and the effects of multiple mitigation measures.

Our results and new information on the diving behavior of white-chinned petrels give cause to reconsider the benchmark depth that delineates the area astern requiring protection with bird-scaring lines in a seabird assemblage dominated by this species. Recall our hypothesis that the aerial extent of bird-scaring lines should span the distance astern of the vessel where baited hooks are available to white-chinned petrels. We set this benchmark depth at 10 m based on a study that measured the maximum diving depth of 11 birds during chick rearing on South Georgia (mean 6.2 m; range 2.8–12.8 m; Huin, 1994) and indirect evidence that a white-chinned petrel intercepted a baited hook beyond 9 m (Melvin et al., 2013). The weighting configuration used in this study sank baited hooks to half our original benchmark depth (5 m) within the 100 m aerial extent of the bird-scaring lines, yet this configuration of bird-scaring lines and weighted branchlines successfully reduced seabird mortality by a factor of seven overall, and eliminated mortality at night.

Recent data on the diving behavior of white-chinned petrels breeding on South Georgia, derived from instruments that recorded depth every second, showed that white-chinned petrels on average dove to less than 3 m in dives lasting fewer than five seconds (British Antarctic Survey, unpublished data); maximum depths were similar (range 3.2–12.2 m, mean = 6.74 m, n = 10, SD = 2.41) to those reported by Huin (1994). These data suggest that white-chinned petrels do not rely on deep diving for foraging and rarely dive beyond 10 m. Collectively this information suggests that a benchmark depth considerably less than 10 m may be sufficient to prevent white-chinned petrel primary attacks on baited hooks. Direct observation of seabird behavior using protocols similar to this study to pinpoint this benchmark depth would be a significant contribution to seabird conservation in the pelagic longline fisheries of the Southern Hemisphere.

Reducing the rate at which the weighted sections of double-weighted branch lines tangle would eliminate the only detectable negative performance attribute of this otherwise successful weighting configuration. Tangling events early in our study were due primarily to the shape of the weights and partly to the stiffness of the coated wire. Spindle-shaped weights cut in half had sharp, flat edges, and the loops at either end of the coated wire were large and prone to tangling. Switching to uncut spindle-shaped weights and a more flexible coated and leaded line (Kodo) allowed for smaller and more flexible loops and substantially less tangling. Our finding, that fish catch rates were similar for weighted and unweighted branch lines, suggests that tangles did not affect fishing success. Fishing masters continue to innovate and improve on the double-weight concept to minimize tangles (Japan Tuna, pers. comm.).

4.3. Secondary bait attacks

Evidence from this study provides compelling and corroborating evidence that secondary attacks – in this system, albatrosses taking baits or baited hooks from white-chinned petrels – drive albatross mortality. The rate of secondary attacks was the most significant factor in our model of bird catch rates and it was significant in all attack rate models unless it was explicitly excluded. Mirroring trends from our 2009 trials (Melvin et al., 2013): (1) white-chinned petrels made 94% of primary attacks on baits, but accounted for only 67% of mortality, (2) albatrosses made only 2% of primary attacks but accounted for 30% of mortality, (3) no shy-type albatrosses were observed making primary attacks yet three were killed, and (4) over half of all primary attacks on baited hooks resulted in secondary attacks.

These findings suggest at least two basic principles for successful seabird bycatch reduction in Southern Hemisphere systems like the South African EEZ: (1) mitigation must exclude or greatly reduce bait attacks by *Procellaria* genus petrels to prevent albatross mortality; and (2) to fully understand the mechanics of seabird bycatch and the effects of mitigation strategies, data collection protocols for evaluating mitigation measures in pelagic longline fisheries should include monitoring secondary attacks. The finding that secondary attack rates were seven times higher on unweighted branch lines illustrates the compounding effect of branch line weighting on albatross mortality. Available evidence suggest that secondary attacks by albatrosses on diving seabirds may be less important in the pelagic longline fisheries of the North Pacific, as these assemblages are dominated by surface foraging albatrosses and lack large diving petrels capable of consuming whole fish or squid baits (Sato et al., 2012, 2013).

If secondary attacks are a proxy – albeit a conservative one – for successful primary attacks, then not only were there fewer primary attacks on weighted branch lines but fewer were successful. Translated to bait loss, this implies that bait loss to birds is more than seven times higher when unweighted lines are used (23.1 vs. 3.3/1000 hooks for unweighted and weighted lines, respectively). If we use all primary attacks as a proxy for the rate of bait loss, bait loss rates nearly double (40.2 baits/1000 hooks) or triple (9.8 baits/1000 hooks) for unweighted and weighted lines, respectively. Clearly, chronic bait loss to birds can lead to hundreds of un-baited hooks being deployed each set.

4.4. Seabird abundance

Consistent with the results of our 2009 trials and counter to other studies (Gilman et al., 2003; Jimenez et al., 2012; Ryan et al., 2002), this experimental study shows that seabird abundance alone, whether during the haul or during the set, did not drive the rate of bait attacks or the rate of bird catch in this system when evaluated in a multivariate framework. This finding suggests that the proposal by Gilman et al. (2005) to weight seabird interaction (attack or catch) rates by the number of birds attending the set as a metric to evaluate seabird bycatch mitigation measures may be inappropriate and misleading. Indexing seabird interactions by abundance also ignores the hierarchical, competitive nature of seabirds at the species and individual levels (Jimenez et al., 2011).

4.5. Fish catch

The catchability of pelagic fish species varies by depth for day and nighttime pelagic longline fishing operations and reflects fish diel vertical migration and changes in visibility (Ward and Myers, 2005). For example, in the North Pacific, the catchability of mesopelagic species such as bigeye and albacore tuna, which are adapted to exploit prey well below the thermocline, increased with depth during the day but less so at night. In contrast, for wide-ranging fishes such as yellowfin tuna, diel variation in catchability by depth was much lower, as they rarely dive below the thermocline due to physiological constraints. In this study, lower fish catch rates during the day (indicated by significance of the day–night factor in the overall model) may have been due to vertical migration and the relatively short hook-soak times of day-setting operations. Short day soaks probably drove the significance of the soak-time factor in the overall fish catch model and the daytime model, and its lack of significance in the night fish catch model. Ultimately, the effects of time of day on fish catch are probably fishery specific and are likely to be a function of the region fished, the hour of night the gear was set and retrieved, and the depth range of the hooks.

This disparity in soak time and diel exposure is also a consideration in interpreting the effects of branch line weighting on fish catch. These results show that, overall, weighting branch lines did not affect target fish catches, as evinced by the insignificance of the weighting factor in the overall and nighttime models. The significance of the weighting and soak-time factors (fewer fish caught on weighted branch lines) in the day model suggests that branch line weighting could reduce fish catch rates during short daytime soaks and that this effect may be species specific (Fig. 7B). The catch rate of bigeye tuna, the high-value species targeted by the fishery, was not affected. Given that pelagic fish are visual predators (Kawamura et al., 1981), we cannot rule out the possibility that weighted branch lines were more conspicuous and led to avoidance by these lesser-value tunas during short daytime soaks. These results suggest that future evaluations of target fish catch in response to seabird bycatch mitigation technologies should consider the effects of time of day and soak time.

4.6. *Bird-scaring lines*

This study provides compelling evidence that two hybrid bird-scaring lines with aerial extents of 100 m were highly effective at preventing seabird attacks within the 100 m aerial extent of bird-scaring lines with or without branch line weighting. No bird attacks by either guild were observed in the area protected by two hybrid bird-scaring lines (within 100 m of the vessel and between the two scaring lines). This result is consistent with a recent comparison of single and paired bird-scaring lines staged in the North Pacific using similar data collection protocols, in which few albatrosses attacked bait within 75 m of the vessel between two bird-scaring lines maintained with aerial extents comparable to those in this study (70–80 m; Sato et al., 2013). Results from our study suggest that, in systems like the North Pacific, where seabird assemblages are less diverse and dominated by shallow diving albatrosses, well designed and correctly deployed bird-scaring lines have the potential to eliminate albatross interactions entirely. Given that 100 m was the maximum bird-scaring aerial extent that could be consistently achieved in our study, aligning the aerial extent of bird-scaring line with the point at which baited hooks sink beyond the access of birds will be achieved through branch line weighting.

The significance of the *weight* factor in both our attack-rate models shows that weighted branch lines affected the reduction of attacks in the area beyond the protection of bird-scaring lines. Ultimately, we conclude that two bird-scaring lines with aerial extents of 100 m forced attacks by diving seabirds to the area beyond 100 m astern of the vessel, and that weighting branch lines significantly reduced diving bird attacks in this area. Unlike our results from bird-scaring line comparisons in 2009, attacks outside the area bounded by two bird-scaring lines were of little importance in 2010. Few attacks occurred there (4.5% of primary and 5.8% of secondary attacks), and most primary attacks (69%) were to port of the port bird-scaring line, close to where baits are deployed. The better performance in 2010 could be attributed to the extended outboard reach of the modified tori poles and/or milder weather.

In this study float lines and bird-scaring lines did get entangled in 5% of sets, but this occurred less frequently than in 2009 (Melvin et al., 2013). We attribute this improvement to replacing the long streamers in the 55–80 m section of the aerial extent with short streamers, and to the efforts of the experienced crews we worked with to fine-tune the arrangement of packing straps in the in-water extent of the lines to be less tangle-prone. Reducing or eliminating tangles while maximizing bird-scaring aerial extent remains one of the primary challenges to the effective and practical use of bird-scaring lines in pelagic longline fisheries.

4.7. *Night setting*

Our finding that the rate of seabird bycatch was dramatically lower on lines set at night than during daylight hours is consistent with our results in 2009 (Melvin et al., 2013) and virtually all analyses of pelagic longline observer data (Baker and Wise, 2005; Brothers et al., 1999b; Gales et al., 1998; Klaer and Polacheck, 1998; Jimenez et al., 2009; Murray et al., 1993; Petersen et al., 2009). However, in the current study two things stand out. Night setting, regardless of branch line weighting, yielded the most dramatic reduction in seabird bycatch; rates were 13 times lower at night (0.028 birds/1000 hooks) than during daylight. No birds were caught on weighted branch lines set at night in 2010, a dramatic improvement over unweighted lines set at night in 2009 (0.439 birds/1000 hooks). Also, this is one of the few studies where moon phase was not a driver of night mortality; only one of three white-chinned petrels was caught within the three nights bracketing the full moon.

We attribute these positive differences to the combined effects of multiple seabird bycatch mitigation measures and to the fine-scale implementation of the study, which allowed us to minimize confounding factors. Although moon phase, season, latitude, and vessel lighting can compromise the effectiveness of night setting as a stand-alone mitigation measure (Baker and Wise, 2005; Brothers et al., 1999b; Gales et al., 1998; Jimenez et al., 2009; Petersen et al., 2009), these results affirm that night fishing can be highly effective at reducing seabird bycatch, especially when used in combination with other mitigation measures.

5. Conclusions

This study comprehensively tested combinations of three primary mitigation measures in a pelagic longline fishery with one of the highest rates of interaction with what may be the world's most challenging seabird assemblage (dominated by *Procellaria* genus petrels), aboard fishing vessels typical of the Asian distant water fleet. We conclude from the results presented here that the simultaneous use of two birds-scaring lines, weighted branch lines and night setting meet our criteria for best-practice seabird bycatch mitigation for the joint venture fleet targeting tuna and related species in the South Africa EEZ. To be successful, the aerial extent of bird-scaring lines should be aligned with the distance astern that baited hooks sink beyond the foraging depth of the dominant seabird – in this case white-chinned petrels to a depth near 5 m. Given that these measures were successful in one of the most challenging pelagic longline fisheries, they are likely to be widely applicable to pelagic longline fisheries using similar gear. Major challenges remain to stemming seabird bycatch in pelagic longline fisheries. At the vessel-fisher level, the imperative is to raise awareness of the need for seabird conservation and how to accomplish it. At the tuna commission level, the challenge is to adopt seabird best practice conservation measures and ensure compliance.

6. Postscript

Seabird-conservation permit conditions for the tuna joint venture fishery were revised for the 2010 and 2011 seasons based on the outcomes of this research program (South Africa, 2012). Fishing masters in the South African joint venture fishery began implementing branch line weighting on a voluntary basis in the 2010 season. In August 2012, the Advisory Committee of ACAP adopted seabird bycatch-mitigation best practices for pelagic longline fisheries consistent with the findings of this research: combined use of hybrid bird-scaring lines, weighted branch lines, and night setting (ACAP, 2011, 2013a). Three tuna commissions (RFMOs) revised their seabird conservation measures for Southern Hemisphere pelagic longline fisheries based on this new ACAP advice (ICCAT, 2011; IOTC, 2012; WCPFC, 2012). Kazuhiro Yamazaki, Fishing Master of the F/V *Fukuseki Maru* No. 5, and host of our research activities from 2008 to 2010, was awarded the 2011 grand prize in the World Wildlife Fund Smart Gear Competition and the special Tuna Prize by the International Seafood Sustainability Foundation for the double-weight branch line configuration he devised in the course of the research (WWF, 2011).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2013.07.012.

References

Agreement on the Conservation of Albatrosses and Petrels (ACAP), 2001. Australian Treaty Series [2004] ATS 5, http://www.austlii.edu.au/au/other/dfat/treaties/2004/5.html (accessed 17.06.13).

ACAP, 2011. Report of the Sixth Meeting of the Advisory Committee Guayaquil, 29 August–2 September 2011 , Ecuador, http://www.acap.aq/index.php/en/documents/doc_download/180-ac6-report-rev-1-2-e (accessed 17.06.13).

ACAP, 2012. Agreement on the conservation of albatrosses and petrels. In: Amended by the Fourth Session of the Meeting of the Parties, 23–27 April 2012, Lima, Peru, http://www.acap.aq/index.php/en/documents/instruments (accessed 17.06.13).

ACAP, 2013a. Report of Seabird Bycatch Working Group. In: Seventh Meeting of the Advisory Committee, 6–10 May 2013. AC7 Doc 14 Rev 1, La Rochelle, France, p. 112, http://www.acap.aq/index.php/en/advisory-committee/doc_download/2135-ac7-doc-14-rev-1-sbwg-report (accessed 17.06.13).

ACAP, 2013b. Report of the population and conservation status working group – PCSWG1. In: Seventh Meeting of the Advisory Committee, 6–10 May 2013. AC7 Doc 12 Rev 1, La Rochelle, France, p. 48, http://www.acap.aq/index.php/en/advisory-committee/doc_download/2130-ac7-doc-12-rev-1-pcswg-report (accessed 17.06.13).

Anderson, S., McArdle, B., 2002. Sink rate of baited hooks during deployment of a pelagic longline from a New Zealand fishing vessel. N. Z. J. Mar. Freshw. Res. 36, 185–195.

Anderson, O.R.J., Small, C.J., Croxall, J.P., Dunn, E.K., Sullivan, B.J., Yates, O., Black, A., 2011. Global seabird bycatch in longline fisheries. Endang. Species Res. 14, 91–106.

Baker, G.B., Wise, B.S., 2005. The impact of pelagic longline fishing on the flesh-footed shearwater *Puffinus carneipes* in Eastern Australia. Biol. Conserv. 126, 306–316.

Baker, G.B., Double, M.C., Gales, R., Tuck, G.N., Abbott, C.L., Ryan, P.G., Petersen, S.L., Robertson, C.J.R., Alderman, R., 2007. A global assessment of the impact of fisheries-related mortality on shy and white-capped albatrosses: conservation implications. Biol. Conserv. 137, 319–333.

Bates, D., Maechler, M., Bolker, B., 2011. lme4: Linear Mixed-effects Models Using S4 Classes. R package Version 0.999375-39, http://CRAN.R-project.org/package=lme4 (accessed 02.01.13).

Boggs, C.H., 2001. Deterring albatrosses from contacting baits during swordfish longline sets. In: Melvin, E.F., Parrish, J.K. (Eds.), Seabird Bycatch: Trends, Roadblocks, and Solutions. University of Alaska, Fairbanks, AK, pp. 79–94 (University of Alaska Sea Grant AK-SG-P 01-L 01).

Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, H.H., White, J-S.S., 2008. Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol. Evol. 24, 127–135.

Breslow, N., 1990. Tests of hypotheses in overdispersed Poisson regression and other quasi-likelihood models. J. Am. Stat. Assoc. 85, 565–571.

Brothers, N., 1991. Albatross mortality and associated bait loss in the Japanese longline fishery in the Southern Ocean. Biol. Conserv. 55, 255–268.

Brothers, N., Cooper, J., Løkkeberg, S., 1999a. The Incidental Catch of Seabirds by Longline Fisheries: Worldwide Review and Technical Guidelines for Mitigation. In: FAO Fisheries Circular No. 937. FAO, Rome.

Brothers, N., Gales, R., Reid, T., 1999b. The influence of environmental variables and mitigation measures on seabird catch rates in the Japanese tuna longline fishery within the Australian Fishing Zone, 1991–1995. Biol. Conserv. 88, 85–101.

Bull, L.S., 2007. Reducing seabird bycatch in longline, trawl and gillnet fisheries. Fish Fish. 8, 31–56.

Bugoni, L., Mancini, P.L., Monteiro, D.S., Nascimento, L., Neves, T.S., 2008. Seabird bycatch in the Brazilian pelagic longline fishery and a review of capture rates in the southwestern Atlantic Ocean. Endang. Species Res. 5, 137–147.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach, 2nd ed. Springer, New York.

Calcagno, V., 2011. glmulti: Model Selection and Multimodel Inference Made Easy. R Package Version 1.0.3, http://CRAN.R-project.org/package=glmulti

Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), 2011. Schedule of Conservation Measures in Force 2011/12 Season. CCAMLR, Hobart, Australia, pp. 99–103.

Catry, P., Phillips, R.A., Phalan, B., Silk, J.R.D., Croxall, J.P., 2004. Foraging strategies of grey-headed albatrosses *Thalassarche chrysostoma*: integration of movements, activity and feeding events. Mar. Ecol. Prog. Ser. 280, 261–273.

Crowder, L.B., Hazen, E.L., Avissar, N., Bjorkland, R., Latanich, C., Ogburn, M.B., 2008. The impacts of fisheries on marine ecosystems and the transition to ecosystem-based management. Annu. Rev. Ecol. Evol. Syst. 39, 259–278, 2008.

Croxall, J.P., Nicol, S., 2004. Management of Southern Ocean fisheries: global forces and future sustainability. Antarct. Sci. 16, 569–584.

Croxall, J.P., Butchart, S.H.M., Lascelles, B., Stattersfield, A.J., Sullivan, B., Symes, A., Taylor, P., 2012. Seabird conservation statis, threats and priority actions: a global assessment. Bird Conserv. Int. 22, 1–34.

FAO, 1995. Code of Conduct for Responsible Fisheries. FAO, Rome, pp. 41, ftp://ftp.fao.org/docrep/fao/005/v9878e/v9878e00.pdf (accessed 23.07.13).

FAO, 1999. International Plan of Action for Reducing Incidental Catch of Seabirds in Longline Fisheries. International Plan of Action for the Conservation and Management of Sharks. International Plan of Action for the Management of Fishing Capacity. FAO, Rome, pp. 26, http://www.fao.org/docrep/006/X3170E/X3170E00.HTM (accessed 23.07.13).

Gales, R., 1998. Albatross populations: status and threats. In: Robertson, G., Gales, R. (Eds.), Albatross Biology and Conservation. Surrey Beatty and Sons, Chipping Norton, NSW, pp. 20–45.

Gales, R., Brothers, N., Reid, T., 1998. Seabird mortality in the Japanese tuna longline fishery around Australia, 1988–1995. Biol. Conserv. 86, 37–56.

Gandini, P., Frere, E., 2012. The economic cost of seabird bycatch in Argentinean longline fisheries. Bird Conserv. Int. 22, 59–65.

Gilman, E., Brothers, N., Kobayashi, D.R., Martin, S., Cook, J., Ray, J., Ching, G., Woods, B., 2003. Performance assessment of underwater setting chutes, side setting, and blue-dyed bait to minimize seabird mortality in Hawaii pelagic longline tuna and swordfish fisheries. In: Final Report. National Audubon Society, Hawaii Longline Association, U.S. National Marine Fisheries Service Pacific Islands Science Center, U.S. Western Pacific Regional Fishery Management Council, Honolulu, HI, USA.

Gilman, E., Brothers, N., Kobayashi, D.R., 2005. Principles and approaches to abate seabird by-catch in longline fisheries. Fish Fish. 6, 35–49.

Hu, F., Shiga, M., Yokota, K., Shiode, D., Tokai, T., Sakai, H., Arimoto, T., 2005. Effects of specifications of branch ling on sinking characteristics of hooks in Japanese tuna longline. Nippon Suisan. Gakkai 71, 33–38.

Huin, N., 1994. Diving depths of white-chinned petrels. Condor 96, 1111–1113.

Indian Ocean Tuna commission (IOTC), 2012. Resolution 12/06: On Reducing The Incidental Bycatch of Seabirds in Longline Fisheries, Collection of Active Conservation and Management Measures for the Indian Ocean Tuna Commission (updated 20.06.12).

International Commission for the Conservation of Atlantic Tunas (ICCAT), 2011. Resolution 11-09. Supplemental Recommendation by ICCAT on Reducing Incidental Bycatch of Seabirds in ICCAT Longline Fisheries.

Jimenez, S., Domingo, A., Brazeiro, A., 2009. Seabird bycatch in the Southwest Atlantic: interaction with the Uruguayan pelagic longline fishery. Polar Biol. 32, 187–196.

Jimenez, S., Domingo, A., Abreu, M., Brazeiro, A., 2011. Structure of the seabird assemblage associated with pelagic longline vessels in the southwestern Atlantic: implications for bycatch. Endang. Species Res. 15, 241–254.

Jimenez, S., Domingo, A., Abreu, M., Brazeiro, A., 2012. Bycatch susceptibility in pelagic longline fisheries, are albatrosses affected by the diving behavior of medium-sized petrels. Aquat. Conserv., Mar. Freshw. Ecosyst., http://dx.doi.org/10.1002/aqc.2242.

Kawamura, G., Nishimura, W., Ueda, S., Nishi, T., 1981. Vision in tunas and marlins. Mem Kagoshima Univ. Res. Center South Pacific 1, 3–47.

Kirby, D.S., Visser, C., Hanich, Q., 2013. Assessment of eco-labelling schemes for Pacific tuna fisheries. Mar. Policy, http://dx.doi.org/10.1016/j.marpol.2013.05.004i.

Klaer, N., Polacheck, T., 1998. The influence of environmental factors and mitigation measures on by-catch rates of seabirds by Japanese longline fishing vessels in the Australian region. EMU 98, 305–316.

Lewison, R.L., Crowder, L.B., Read, A.J., Freeman, S.A., 2004. Understanding impacts of fisheries bycatch on marine megafauna. Trends Ecol. Evol. 19, 598–604.

Løkkeberg, S., 2008. Review and assessment of mitigation measures to reduce incidental catch of seabirds in longline trawl and gillnet fisheries. Food and Agriculture Organization of the United Nations, Rome (FAO Fisheries and Aquaculture Circular No. 1040).

Løkkeberg, S., 2011. Best practices to mitigate seabird bycatch in longline, trawl and gillnet fisheries – efficiency and practical applicability. Mar. Ecol. Prog. Ser. 435, 285–303.

Mackley, E.K., Phillips, R., Silk, J.R.D., Wakefield, E.D., Afanasyev, V., Furness, R.W., 2011. At-sea activity patterns of breeding and nonbreeding white-chinned petrels *Procellaria aequinoctialis* from South Georgia. Mar. Biol. 158, 429–438.

Melvin, E.F., Robertson, G., 2000. Appendix 3: seabird mitigation research in longline fisheries: status and priorities for future research and actions. In: Cooper, J. (Ed.), Albatross And Petrel Mortality From Longline Fishing, International Workshop, Marine Ornithology. Vol. 28, 11–12 May 2000. Honolulu, HI, pp. 178–181.

Melvin, E.F., Parrish, J.K., Dietrich, K.S., Hamel, O.S., 2001. Solutions to Seabird Bycatch in Alaska's Demersal Longline Fisheries. Washington Sea Grant, WSG-AS 01-01, http://wsg.washington.edu/communications/online/seabirds/seabirdpaper.html (accessed 31.12.12).

Melvin, E.F., Sullivan, B.J., Robertson, G., Wienecke, B., 2004. A review of the effectiveness of streamer lines as a seabird bycatch mitigation technique in longline fisheries and CCAMLR streamer line requirements. CCAMLR Sci. 11, 189–201.

Melvin, E.F., Guy, T.J., Read, L.B., 2010. Shrink and defend: a comparison of two streamer line designs in the 2009 South Africa tuna fishery. In: ACAP SBWG-3 Doc13. Rev1, http://www.acap.aq/index.php/en/working-groups/cat_view/128-english/59-working-groups/60-seabird-bycatch-working-group/305-seabird-bycatch-wg-meeting-3/306-sbwg3-meeting-documents (accessed 23.07.13).

Melvin, E.F., Guy, T.J., Read, L.B., 2013. Reducing seabird bycatch in the South African joint venture tuna fishery using bird-scaring lines, branch line weighting and nighttime setting of hooks. Fish. Res. 147, 72–82.

Murray, T.E., Bartle, J.A., Kalish, S.R., Taylor, P.R., 1993. Incidental capture of seabirds by Japanese southern bluefin tuna longline vessels in New Zealand waters, 1988–1992. Bird Conserv. Int. 3, 181–210.

Petersen, S.L., Honig, M.B., Ryan, P.G., Underhill, L.G., 2009. Seabird bycatch in the pelagic longline fishery off southern Africa. Afr. J. Mar. Sci. 31, 191–204.

Phalan, B., Phillips, R.A., Silk, J.R.D., Afanasyev, V., Fukuda, A., Fox, J., Catry, P., Higuchi, H., Croxall, J.P., 2007. Foraging behaviour of four albatross species by night and day. Mar. Ecol. Prog. Ser. 340, 271–286.

Phillips, R.A., 2013. Requisite improvements to the estimation of seabird by-catch in pelagic longline fisheries. Anim. Conserv. 16, 157–158.

R Development Core Team, 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0, http://www.R-project.org/ (accessed 01.02.13).

Robertson, G., Candy, S.G., Wienecke, B., Lawton, K., 2010. Experimental determinations of factors affecting the sink rates of baited hooks to minimize seabird mortality in pelagic longline fisheries. Aquat. Conserv., Mar. Freshw. Ecosyst. 20, 632–643.

Robertson, G., Candy, S.G., Hall, S., 2013. New branch line weighting regimes to reduce the risk of seabird mortality in pelagic longline fisheries without affecting fish catch. Aquat. Conserv., Mar. Freshw. Ecosyst., http://dx.doi.org/10.1002/aqc.2346.

Ryan, P.G., Keith, D.G., Krose, M., 2002. Seabird bycatch by tuna longline fisheries off Southern Africa, 1998–2000. S. Afr. J. Mar. Sci. 24, 103–110.

Ryan, P.G., Rose, B., 1995. Migrant seabirds. In: Payne, A.I.L., Crawford, R.J.M. (Eds.), Oceans of Life off Southern Africa, 2nd ed. Vlaeberg Publishers, Vlaeberg, Cape Town, pp. 274–287.

Sánchez, A., Belda, E.J., 2003. Bait loss caused by seabirds on longline fisheries in the northwestern Mediterranean: is night setting an effective mitigation measure? Fish. Res. 60, 99–106.

Sato, N., Ochi, D., Minami, H., Yokawa, K., 2012. Evaluation of the effectiveness of light streamer tori-lines and characteristics of bait attacks by seabirds in the western North Pacific. PLoS ONE 7 (5), e37546, http://dx.doi.org/10.1371/journal.pone.0037546.

Sato, N., Minami, H., Nobuhiro, K., Ochi, D., Yokawa, K., 2013. Comparison of the effectiveness of paired and single tori lines for preventing bait attacks by seabirds and their bycatch in pelagic longline fisheries. Fish. Res. 140, 14–19.

Smith, A.D.M., Fulton, E.J., Hobday, A.J., Smith, D.D., Shoulder, P., 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. ICES J. Mar. Sci. 64, 633–639.

South Africa, 2010. Section B. Permit Conditions: Tuna Longline Fishery. Fishing Season: 2010/2011. Agriculture, Forestry and Fisheries, Republic of South Africa, pp. 28.

South Africa, 2012. Section B. Permit Conditions: Tuna Longline Fishery. Fishing Season: 2012/2013. Agriculture, Forestry and Fisheries, Republic of South Africa, pp. 41, http://www.nda.agric.za/doaDev/fisheries/21_HotIssues/April2010/FishingPermitsConditions2012/TLL%20~2012-13.pdf (accessed 23.07.13).

Tuck, G.N., Polacheck, T., Croxall, J.P., Weimerskirch, H., 2001. Modelling the impact of fishery bycatches on albatross populations. J. Appl. Ecol. 38, 1182–1196.

Tuck, G.N., Polacheck, T., Bulman, C.M., 2003. Spatio-temporal trends of longline fishing effort in the Southern Ocean and implications for seabird bycatch. Biol. Conserv. 114, 1–27.

Ward, P., Myers, R.A., 2005. Inferring the depth distribution of catchability for pelagic fishes and correcting for variations in the depth of longline fishing gear. Can. J. Fish. Aquat. Sci. 62, 1130–1142.

Weimerskirch, H., Brothers, N., Jouventin, P., 1997. Population dynamics of wandering albatross *Diomedea exulans* and Amsterdam albatross *D. amsterdamensis* in the Indian Ocean and their relationships with longline fisheries: conservation implications. Biol. Conserv. 75, 257–270.

Western Central Pacific Fisheries Commission (WCPFC), 2012. Conservation and management measure to mitigate the impact of fishing for highly migratory fish stocks on seabirds, conservation and management measure 2012-07. In: Commission ninth regular session, 2–6 December 2012, Manila, Philippines, http://www.wcpfc.int/doc/CMM-2012-07/Conservation-and-Management-Measure-Mitigating-Impacts-Fishing-Seabirds (accessed 26.06.13).

World Wildlife Fund (WWF), 2011. SmartGear Grand Prize Winner 2011, http://www.smartgear.org/smartgear_winners/2011/grand_prize (accessed 02.02.13).

Yokota, K.M., Minami, H., Kiyota, M., 2008. Direct comparison of seabird avoidance effect between two types of tori lines in longline fishing experiments. In: Scientific Committee, Fourth Regular Session, Western and Central Pacific Fisheries Commission, Port Moresby, Papua New Guinea. WCPFC-SC4-2008/EB-W P-7, http://www.wcpfc.int/../SC4-EB-WP7%20%5BTori%20lines%5D.pdf (accessed 11.07.13).

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology. R. Springer, New York.