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At-sea trialling of the Hookpod: a ‘one-stop’ mitigation solution for seabird bycatch in pelagic longline fisheries

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Abstract

Bycatch of pelagic seabird species in longline fisheries is recognized as one of the most important and pervasive sources of mortality, contributing to an increased risk of their extinction. Uptake of mitigation measures to reduce seabird bycatch has not been widespread by the industry. Here, we present the results of 18 at-sea trials conducted between 2011–2015 onboard pelagic longliners targeting tuna (*Thunnus* spp) and swordfish (*Xiphias gladius*) in South African, Brazilian and Australian waters, using a recently designed seabird bycatch mitigation device. The ‘Hookpod’ is a polycarbonate capsule that encases the point and barb of baited pelagic longline hooks to prevent seabirds from becoming hooked and drowning during line-setting operations. The assessment was based on efficacy (i.e. reducing rates of seabird bycatch without impacting target catch rate) and practicality (i.e. how the Hookpod fitted into fishing operations). We observed 59 130 experimental branchlines over 129 sets and recorded a single seabird mortality on the Hookpod branchlines compared to 24 on the control branchlines, a bycatch rate of 0.04 birds/1000 hooks and 0.8 birds/1000 hooks, respectively. No difference in catch rate of target fish species between Hookpod and control treatments was detected. These findings demonstrate that Hookpods do not negatively affect catch rate of target species and could make an important contribution to halting the decline of many seabird populations if adopted as a mitigation measure by the pelagic longline fishing industry.

Introduction

Currently, 15 out of 22 species of albatrosses are threatened with extinction (BirdLife International, 2015). Bycatch of these and other seabird species in longline and trawl fisheries is recognized as one of the most important and pervasive sources of mortality, contributing to an increased risk of their extinction (Brothers, 1991; Nel, Ryan & Watkins, 2002; Sullivan, Reid & Bugoni, 2006; Anderson *et al.*, 2011; Melvin, Guy & Read, 2013). In demersal longline and trawl fisheries, mitigation solutions to seabird bycatch have been highly effective, and in some cases have virtually eliminated seabird bycatch (Croxall, Rivera & Moreno, 2007; Croxall *et al.*, 2012; Maree *et al.*, 2014). However, in the case of pelagic longline fisheries, and in particular high seas tuna fisheries, the uptake of mitigation measures has been limited (Croxall, 2008; Robertson, 2017). Pelagic gear is designed to float in the water column and by necessity is lightweight in nature. However, considerable research has been undertaken to test line weighting regimes and techniques to increase the sink rate of pelagic gear (Robertson *et al.*, 2010; Melvin, Guy & Read, 2014). It is widely recognized that a combination of measures is required to effectively reduce seabird bycatch in pelagic fisheries (FAO, 1999, 2009; Løkkeberg, 2008; Melvin *et al.*, 2014). Current best practice mitigation advice for pelagic longline fisheries developed by the Agreement on the Conservation of Albatrosses and Petrels (ACAP) states that ‘best-practice advice for mitigating seabird bycatch in pelagic longline fisheries is to use the following three measures simultaneously: branchline weighting, night setting and bird scaring lines'. However, in April 2016, the Ninth Meeting of the ACAP Advisory Committee added 'hook-shielding devices' (which includes the Hookpod) to their list of best practice measures for mitigating seabird bycatch in pelagic longline fisheries (ACAP, 2016).

In recent years, there have been several attempts to simplify the operational complexity of using multiple mitigation measures to mitigate seabird bycatch in pelagic longline fisheries by developing a single mitigation measure. For example, baited hooks have been delivered at depth using line setting devices attached to the stern of the vessel, an approach that was demonstrated in at-sea trails to be effective at reducing seabird bycatch in pelagic (Gilman, Boggs & Brothers, 2003) and demersal (Løkkeborg, 2003) fisheries. However, these devices have faced a range of engineering and operational challenges that have impeded their development (Ryan & Watkins, 2002; Bull, 2007; Løkkeberg, 2008), and have not achieved commercial adoption by the fishing industry. More recently, two new technologies to reduce seabird bycatch are undergoing final at-sea testing (1) a stern-mounted, hydraulically operated and computer-controlled capsule that delivers baited hooks below the surface (Robertson *et al.*, 2014), and (2) a hook-shielding device with a dissolvable pin that releases the baited hook within 10 minutes of being set (Baker, Candy & Rollinson, 2016).

Here, we present the results of at-sea testing of a new single-mitigation measure (the 'Hookpod') for reducing seabird bycatch in the pelagic longline fishing industry. We conducted 18 at-sea trips in three regions (South Africa, southern Brazil and Australia) comparing seabird bycatch rates and the catch rate of target and non-target species caught using branchlines with Hookpods compared to branchlines with line weighting. The Hookpod is loaded on deck and cast to the water's surface, thereby avoiding the engineering challenges faced by underwater setting devices. In designing the Hookpod, we were guided by the following key principles:

(1) a high degree of effectiveness in reducing seabird bycatch;
(2) no reduction in target catch rate, and
(3) cost-effective and operationally simple to use for the end-user (fishermen).

Materials and methods

Hookpod design and deployment

The Hookpod is a polycarbonate capsule that is attached to a monofilament branchline. During line setting operations the baited hook is loaded into the Hookpod to encase the point and barb of the hook; preventing seabirds from becoming hooked as they scavenge for baits at the stern of vessel. The device contains a pressure release system that opens the Hookpod and releases the baited hook at a predetermined depth of 10 m (Figs 1 and 2). This depth threshold was based on the maximum diving depth beyond which it was considered feasible for a diving seabird to retrieve a branchline with a baited hook and Hookpod to the surface, thereby making it accessible to larger, non-diving seabirds such as albatrosses. On hauling, the Hookpod remains attached to the branchline in an open state and is rearmed by closing it by hand. It is then stored in the setting bin, ready for the next set.

The Hookpod includes a light-emitting diode (LED), which operates on a magnetic switch that is triggered when the pod opens at depth to release the baited hook. The LED is powered by two small, alkaline (AG13 LR44) cell batteries that operate for up to 400 h (around 40+ sets). The batteries cost approximately US$0.10 each and are quick to replace. The LED was incorporated to provide a financial incentive to fishermen by offering an alternative light source that replaces the disposable chemical light sticks that are used in swordfish and many tuna fisheries globally. In recent years the use of battery powered LED fishing lights has become more common and these range from US$30 for lights attached to the mainline that provides a light source for several hooks, to smaller, less powerful and much cheaper options that attach to individual branchlines.

The pod has been designed to last for several years under typical fishing operations. The polycarbonate material used for the housing is extremely durable and resistant to damage by ultra violet (UV) rays and seawater and all hinges and springs are made from marine grade 316 stainless steel. It is estimated that when in commercial production that Hookpods will cost around US$8.50 per unit, which based on an average 1000 branchlines used in domestic pelagic longline fleets represents an initial capital cost of US$8500 per vessel. Discussions with fishermen in Australia and Brazil indicate that the annual cost of chemical lightsticks can exceed US $20 000 and US$15-20 000, respectively (B. Sullivan & F. Peppes, pers. comm.). In fisheries that use chemical light sticks, the annual operational costs of Hookpods will be readily off-set in cost savings from reduced use of light sticks.

Data collection

Eighteen at-sea trials of the Hookpod were conducted on seven pelagic longline vessels targeting a range of tuna species and swordfish between 2011 and 2015 in three geographically distinct regions (South Africa, southern Brazil and Australia) (Table 1). Vessels used the American longline system and were a mixture of steel and wooden construction and ranged from 15 m to 28 m in length and 80–165 metric tonnes. The smaller class of vessels were used in Brazil and Australia and the larger vessels in South Africa. The three regions were selected for trials for two primary reasons. Firstly, southern Brazil and South Africa are widely regarded as global hotspots for incidental captures of albatrosses and petrels (Bugoni *et al.*, 2008; Petersen *et al.*, 2010; Anderson *et al.*, 2011) and secondly, Australia was selected for trials because the Eastern Tuna and Billfish Fishery (ETBF) has a proven record of pro-active engagement with the development and implementation of new measures and technologies to reduce fisheries bycatch.

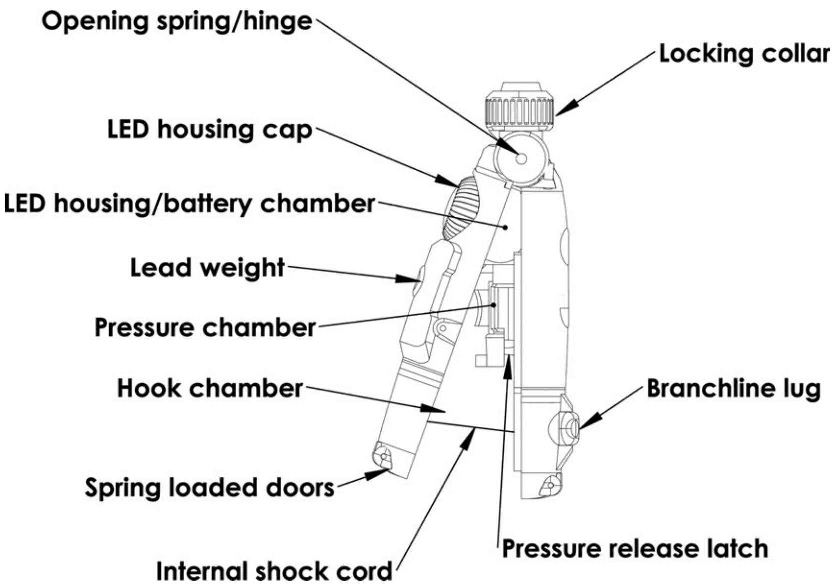

Figure 1 Components of the Hookpod.

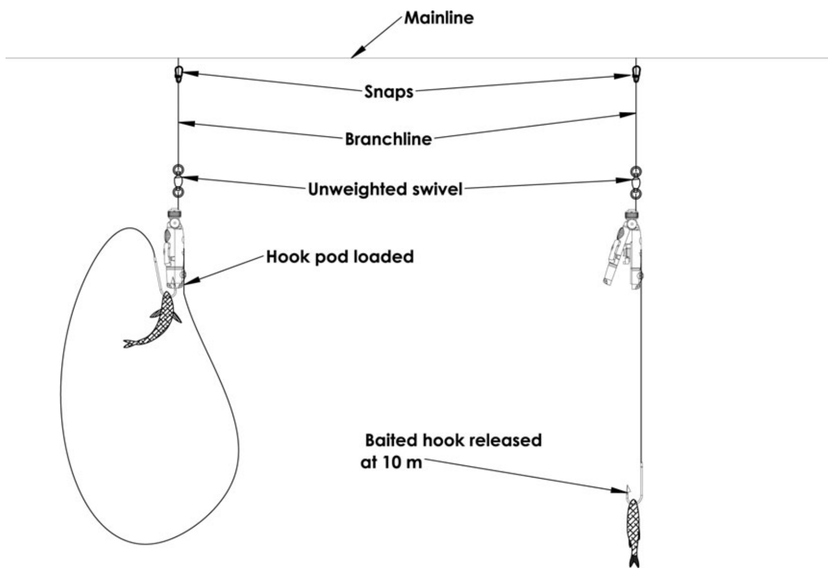

Figure 2 The Hookpod *in situ* prior to and after the pressure release mechanism opens the pod.

All trips were conducted with a dedicated observer onboard who observed all experimental hooks during line setting and hauling. The sampling design was based on two treatments: (1) Hookpod branchlines included a 65 g Hookpod (incorporating a 15 g lead weight) and LED attached below an unweighted swivel that was positioned 1–7 m (depending on in-country fishery regulations) from the hook, and (2) control branchlines had weighted swivel ranging from between 60–80 g, placed at 2–7 m (depending on in-country fishery regulations) from the hook, plus a chemical light stick. For minor deviations from the standard design, see Table 1.

Experimental branchlines constituted only a portion of each set. Alternating treatment blocks of Hookpod and control branchlines were deployed, with the first treatment assigned randomly. The number of blocks of each treatment varied between trips and ranged from 1 to 4. While the size of treatment blocks was equal within each set it varied between trips from 40 to 240 of each type of branchline. This variation in the number and size of treatment blocks was due to operational issues related to deck space and the placement of setting boxes that were unique to each vessel. All experimental lines (Treatments 1 and 2) were set in the absence of bird scaring lines under scientific permit. As experimental branchlines only constituted a proportion of each set, non-experimental branchlines within each set had a streamer line deployed. Line setting occurred predominantly

Table 1 Eighteen at-sea trips were conducted in three regions between 2011 and 2015. Multiple sets were conducted in each trip, and the number of hooks deployed for each treatment per set and trip differed. Hookpod branchlines were set with LEDs within the Hookpod and control branchlines with light sticks. Treatment 3 and Treatment 4 were Hookpods without LEDs and standard control hooks without light sticks, respectively

				#Hooks	
Region	Trip	Month-Year	Sets	Hookpods	Control
South Africa	1	Feb-2012	5	1200	1200
South Africa	2	Mar-2012	10	2400	2400
South Africa	3	Jun-2012	14	3997	4143
South Africa	4	Aug-2012	10	2052	1991
South Africa	5	Oct-2014	15	3159	3043
Subtotal	5		54	12 808	12 777
Brazil	1	Jul-2011	7	1357	1456
Brazil	2	Jun-2013	3	300	300
Brazil	3	Jun-2013[a]	3	774	726
Brazil	4	Jul-2013	8	2140	2140
Brazil	5	Aug-2013	9	1798	1844
Brazil	6	Sep-2013	6	1075	1075
Brazil	7	Sep-2013	13	1375	1375
Subtotal	7		49	8819	8916
Australia	1	Oct-2014	2	1660	1640
Australia	2	Oct-2014[b]	3	790	780
Australia	3	Dec-2014	2	830	2230
Australia	4	Jan-2015	3	1140	3450
Australia	5	Jul-2015	7	2193 (Treatment 3)	2286 (Treatment 4)
Australia	6	Sep-2015	3	270	270
Subtotal	6		26	6065	9745
Total	18		129	27 692	31 438

[a]Hookpods were inverted (turned upside down) for Trip 3.
[b]Hookpods were placed above weighted swivel for Trip 2.

in daylight hours with some setting operations starting at around dusk and continuing into the night.

Seabird abundance counts were conducted for 5 min periods in an area 50 m × 200 m from the stern of the vessel at the beginning of each line setting operation conducted during daylight hours.

We worked with in-country government agencies and industry to obtain the required approvals and scientific permits. To prevent excessive seabird mortalities *a priori* species-specific seabird bycatch thresholds were established. It was agreed that exceeding any of the following mortality threshold levels in a single research trip would lead to the trials being suspended: 15 albatross species of the genus *Thalassarche*, 15 *Procellaria* petrels or five *Diomedea* albatrosses.

In total, 59 130 hooks were set during the trials, with virtually equal ratio between treatments (Table 1). For Hookpod and control branchlines, the fish caught (both target and non-target species) were identified to the species level. In addition, all seabird mortalities were recorded to species level.

Bait and hook type and hooking position

During the course of our experimental trials a range of bait types, sizes and hooking positions were trialled. All hook types used were circle hooks size 15/0 and 16/0**.** Bait used included Argentine shortfin squid *Illex argentinus*, slimy mackerel *Scomber australasicus*, chub mackerel *Scomber japonicas*, yellow-tailed mackerel *Trachurus novaezelandiae,* Brazilian sadinelle *Sardinelle brasileiensis* and pilchard *Sardinops sagax*. The type of bait used in each set was proportionally equal between treatments. In addition, we trialled 'eye hooking', 'back-hooking' and during trials in the ETBF in 2014 we also trialled 'live bait' using slimy mackerel and yellow-tailed mackerel.

Sink rate

It is important to note that when the 65 g Hookpod is loaded the weight is directly on the hook, until it reaches 10 m when it opens and the baited hook falls out. During trials in the ETBF, we investigated the sink rate of baited hooks for Hookpod and control branchlines (60 g lead swivel placed 3.5 m from the hook) using time-depth-recorders (TDRs, Wildlife Computer MK9) added to a selection of branchlines. It has been demonstrated in the same fishery that MK9 TDRs do not affect the final sink rate of branchline (Robertson *et al.*, 2010). Time-depth-recorders were attached adjacent to the Hookpod or 15 cm from the hook on control branchlines that were close to the mid-point between mainline floats.

Data analysis

Assessing fish catch rate

Individual fish species caught were grouped into family cohorts, as data were too sparse for single-species analyses. Family cohorts were: 'Target Tuna' – including the Yellowfin tuna *Thunnus albacares*, bigeye tuna *Thunnus obesus*, albacore *Thunnus alalunga*, and southern bluefin tuna *Thunnus maccoyii*; 'Swordfish' – *Xiphias gladius*; 'Shark' – contained all shark species (shortfin mako, *Isurus oxyrinchos* and longfin mako, *Isurus paucus*; Blue shark *Prionace glauca*, smooth hammerhead *Spyrna zygaena*), and 'Other' – contained all other species (dominated by Ray's Bream *Brama brama*, striped marlin *Kajikia audax*; dolphinfish *Coryphaena hippurus*, barracouta *Thyrsites atun,* and skipjack tuna *Katsuwonus pelamis*).

Generalized linear mixed models were fitted (Brown & Prescott, 2004; Bates & Maechler, 2009) treating the catch-rate of each family cohort response variable as an independent binomial trial, that is, the number of animals caught in each family cohort divided by the total number of experimental hooks set per branchline (i.e. effort per hook). Branchline type was considered as a fixed effect, and the random component of the model was Set nested within Trip. This random effects structure was used to account for the hierarchical survey design and correlation of observations within a single trip during which multiple sets were deployed. The error structures of the random and fixed effects were investigated but found to have minimal impact on model conclusions (results not presented, but further rationale is provided in the Discussion). Models were fitted using the 'glmer' function within the 'lme4' package (34, v.1.1-12) in the statistical software program R (v.3.2.2, www.cran.r-project.org).

Assessing the effect of Hookpods without LEDs and control branchlines without light sticks

Many tuna fisheries do not use a light source to attract bait fish, so in July 2015 we conducted trials in the Australian ETBF to investigate the effect of Hookpods without LEDs compared to control branchlines with no light sticks when targeting albacore. The trial design consisted of Hookpod branchlines deployed without operational LEDs (Treatment 3), and control branchlines deployed without light sticks (Treatment 4). Catch rates between Treatments 3 and 4 were compared to each other using a non-parametric Wilcoxon Rank Sum test.

Results

Seabird assemblages and by-catch

The seabird assemblages encountered during our trials varied greatly between season and fishery. The following descriptions provide an overview by fishery of the species that dominated the seabird assemblages associated with vessels in each of the three regions.

In Brazil, seabird assemblages were characterized by white-chinned petrels *Procellaria equinoctialis*, spectacled petrel *Procellaria conspicillata,* black-browed albatross *Thalassarche melanophris*, Atlantic yellow-nosed albatross *Thalassarche chlororhynchos* and seasonally, wandering albatross *Diomedea exulans*, Tristan albatross *Diomedea dabbenena*, northern Royal albatross *Diomedea sanfordi* and southern Royal albatross *Diomedea epomophora.*

In South Africa, seabird assemblages were dominated by cape Petrel *Daption capense*, black-browed albatross, white-chinned petrels, and seasonally, Atlantic yellow-nosed albatross and wandering albatross.

In Australia, the diversity of seabirds associated with vessels during our trials were typically lower than in the other two fisheries, and were dominated by flesh-footed shearwaters *Puffinus carneipes*, sooty shearwaters *Ardenna grisea*, black-browed albatross and the shy albatross *Thalassarche cauta*.

In this study, 59 130 hooks were set, distributed across 129 sets, 18 trips and three regions. Twenty-five birds were killed in these trials, in 11 separate sets. Most were single mortalities but 14 birds were killed on one set (Table 2). Twenty-four of the 25 bird deaths occurred on control branchlines. This represents a total bycatch rate of 0.8 birds/1000 hooks for control branchlines, compared to a catch rate of 0.04 birds/1000 hooks on Hookpod branchlines. Only one seabird was killed on Hookpod branchlines, making statistical modelling unreliable.

Three albatross were killed on Hookpod branchlines in South Africa (Trip 5), however, this occurred during a single hauling operation (not during line setting) when a killer whale *Orcinus orca* caused a serious entanglement in the mainline and the crew went to lunch, leaving hooks near the surface for an extended period. These mortalities were not included in our analysis.

Assessing fish catch rate

Regardless of region and year, boxplots for all family cohorts suggest the distribution of catch rate between treatment types are overlapping, and reveal large variability in catch rate between trips (Supporting Information Fig. S1). There were no significant differences in catch rates of target species between treatments (Table 3).

Assessing the effect of Hookpods without LEDs and control branchlines without light sticks

During July 2015, a single trip consisting of 7 sets of each treatment type was conducted in Australian waters. Tuna and Other were the only family cohorts for which enough data were obtained to provide any insight into whether Hookpods branchlines without LEDs, and control branchlines without light sticks had differing catch rates. We compared the two types of branchlines to each other, using a Wilcoxon rank-sum test and no significant difference

Table 2 Number of seabirds killed in experimental trials by region and treatment

Region	Trip No.	T1 (Hookpods)	T2 (control)	IUCN status
Australia	2		1 black-browed albatross	Near Threatened
Australia	3		1 black-browed albatross	Near Threatened
Brazil	2		1 black-browed albatross	Near Threatened
Brazil	3		1 white-chinned petrel	Vulnerable
			1 black-browed albatross	Near Threatened
Brazil	4	1 white-chinned petrel	12 black-browed albatross	Near Threatened
			1 white-chinned petrel	Vulnerable
			2 southern royal albatross	Vulnerable
				Vulnerable
Brazil	5		2 black-browed albatross	Near Threatened
Brazil	6		1 black-browed albatross	Near Threatened
South Africa	5		1 shy albatross	Near Threatened

Table 3 Coefficient estimate (standard error) for control branchlines, 95% confidence interval and associated test statistics for each of the four family cohorts

	Tuna	Swordfish[a]	Sharks	Other
Estimate (SE)	−0.06 (0.05)	−0.02 (0.11)	−0.14 (0.05)	−0.21 (0.09)
95% CI	(−0.15, 0.03)	(−0.23, 0.19)	(−0.25, −0.04)	(−0.39, −0.03)
z	−1.32	−0.19	−2.72	−2.27
P-value	0.186	0.850	0.006	0.023

[a]Swordfish analysis excluded Australian region, as data there were too sparse.

between the treatment groups were detected for either family cohort (*P*-values >> 0.1, results not presented, Fig. 3).

Sink rate

The TDRs indicated that the baited hook inside the Hookpods sank to two metres at 0.47 m s^{-1}, which is around twice the speed of the control branchlines (T2, 0.24 m s^{-1}), and to five metres at slightly less than twice the speed of the control branchlines (T2, 0.51 m s^{-1} vs. 0.31 m s^{-1}) (Table 4). Interestingly, at around 10 m the sink rate of the Hookpod branchlines was equivalent to the control branchlines This is likely to be caused by the Hookpod opening up to release the hook and the 'wing' of the pod acting like a parachute under water, and thereby slowing the sink rate of the Hookpod when compared to the sink rates higher in the water column.

Turtle bycatch

In total, 31 sea turtles were caught on experimental branchlines. A single Leatherback turtle *Dermochelys coriacea* was caught on control branchlines in both Australia and South Africa. In Brazil between June and September 2013, 29 Loggerhead turtles *Caretta caretta* were caught. Nine were caught on Hookpod branchlines and 20 on control branchlines.

Discussion

Seabird and turtle bycatch

The Hookpod was found to be highly effective at reducing seabird bycatch in pelagic longline fisheries. The comparative seabird bycatch rates of 0.8 birds/1000 hooks for control branchlines, compared to a rate of 0.04 birds/1000 hooks on the Hookpod branchlines were collected from a range of pelagic longline fisheries, two of which are considered amongst the world's 'worst case scenario' fisheries for seabird bycatch (southern Brazil and South Africa). The single record of a seabird mortality on Hook branchlines (Table 2) was recorded in Brazil and the observer noted that the hook was not loaded correctly into the Hookpod.

Although the trials were not designed to explore impacts on turtle bycatch, the high levels of turtle bycatch in Brazil in these trials and subsequent trials in 2017 (not reported here) and the marked reduction in turtle bycatch on Hookpod branchlines has led to the planning of further trials. Those trials would involve a modified Hookpod that opens at 20 m depth, to investigate if this can further reduce turtle bycatch.

Assessing fish catch rates

We found no difference in the catch rate of target fish species caught, using the Hookpods compared to control branchlines. In the models fitted, we assumed the catch-rate of each family cohort response variable was an independent binomial trial. Clearly, there is competition between fish for hooks, and this competition process violates the assumption of independence. However, the catch rates across the 18 trips were low, and sets never reached a near-saturation point of all hooks taken by fish so it is reasonable to assume independence between the trials.

For non-target species, the catch rate of 'Other' increased on Hookpod branchlines, which was primarily driven by a

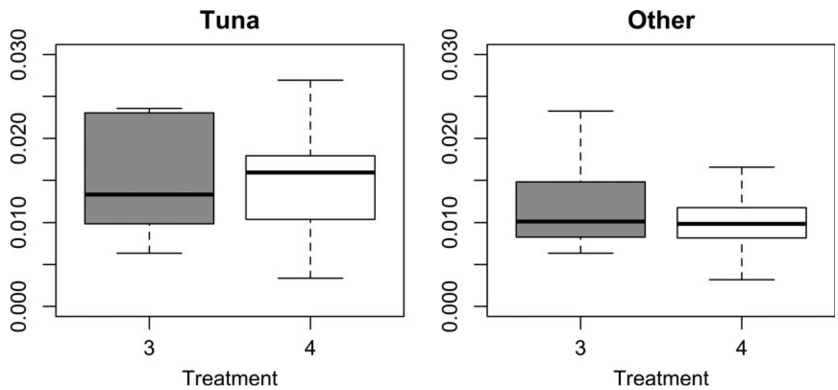

Figure 3 Catch rate per unit effort for Tuna and Other for Treatment 3 (Hookpods without LEDs) and Treatment 4 (standard branchlines without light sticks).

Table 4 Sink rate (m s^{-1}) for Hookpods and 65 g weighted swivel placed at 3.5 m from the hook down to two, five and ten metres. *N* is the sample size

	Weighted swivel			Hookpod			
Depth	*N*	Mean	SE	*N*	Mean	SE	CI
2 m	5	0.240	0.045	12	0.472	0.037	(0.028, −0.18)
5 m	5	0.312	0.034	12	0.508	0.031	(−0.23, −0.16)
10 m	5	0.288	0.062	12	0.224	0.040	(−0.00006, 0.13)

relatively high catch rate of Ray's Bream on two trips conducted in Australia in 2014. Importantly, this increase in a single non-target species did not significantly reduce the catch rate of the target (tuna) species. Similarly, the significant difference in shark catch rates was driven primarily by a single trip in South Africa in October 2014 (Table 1, trip 5) when significantly more sharks were caught on both Hookpod and control branchlines than any other trip (990 sharks in total, compared to 196 sharks on trip 3, and 167 sharks combined for trips 1, 2 and 4).

During our single trip in the ETBF in July 2015 (Table 1, trip 5) we conducted 7 sets without a light source on either type of branchline (Treatments 3 and 4) and detected no significant difference in catch rate of target species. This suggests that Hookpods without LEDs catch as many target species as standard branchlines without light sticks. There was insufficient data on shark catch rate for a reliable analysis.

Utility of the Hookpod

Our trials were conducted on multiple vessels in three distinct fisheries. While it typically takes a few sets for the crew to adapt to the use of Hookpods, once this occurs setting operations can be conducted at normal speed. The time taken to load the baited hook into the Hookpod can be offset by the time saved not attaching a light stick.

In pelagic longline fisheries, one of the most difficult issues to solve is 'secondary hook-ups'. These can occur when deep diving birds (e.g. shearwaters and *Procellaria* petrels) return baited hooks to the surface where they become available to larger birds, such as, albatross (Jiménez *et al.*, 2012). We tested Hookpods in fisheries associated with 'worst case scenario' seabird assemblages for bycatch. These assemblages were dominated by white-chinned petrels and *Puffinus* shearwaters, which are recognized as two of the most difficult seabird species to deter from baited hooks (Robertson *et al.*, 2006; Jiménez *et al.*, 2012; Melvin *et al.*, 2013), and a range of albatross species. Our sink rate data indicates that the sink rate of Hookpods down to 2 and 5 m depths is almost doubled when compared to control branchlines (60 g at 3.5 m, Table 4). It is important to note that the slowing of the sink rate on Hookpod branchlines once the Hookpod opens at 10 m depth does not result in pods being returned to the surface where they can be accessed by larger non-diving species, such as albatross.

Our biggest challenge in terms of the durability of the pod was that in some cases when a fish was caught on a branchline the force of the water created by the fish fighting was enough to break the open side/'wing' (see Fig. 1) of the pod. In many cases this caused the 'wing' to sheer off, or for the polycarbonate housing around the edges of the LED housing to crack.

In December 2014, we incorporated an internal 'shock cord' (Fig. 1) low down in the housing of the pod. This absorbed the pressure created by a large fish swimming (fighting) rather than the drag force being transferred up the 'wing' of the pod towards the opening spring-hinge. Controlled, destruction force tests conducted on-shore demonstrated that the pod was 3 times stronger with the shock cord included compared to the previous prototypes. It was at this point, after 6 years of development and trialling, that we were able to commence our tolerance testing.

Based on a cost–benefit analysis of the economics of the Hookpod for fishermen, we established an *a priori* threshold rate for device failure of around 1% over 5000 repetitions. Since the inclusion of the internal shock cord in December 2014, we have conducted over 6065 Hookpod branchline repetitions on three vessels in Australia. This includes additional trips not reported in Table 1 between February and May 2015 when no fish catch rate data were collected as there was no observer onboard. However, the skipper was diligent in recording full details of all Hookpod breakages and/or failures (not opening, not closing) and these have been included when deriving our tolerance testing results. Since December 2014, we achieved a total failure rate of 1.23%.

Fisheries that do not use lights to attract bait fish could still potentially have considerable operational advantages from using Hookpods. For example, they could remove the need for the use of bird scaring lines and or weighted swivels in their branchlines. In some cases, restrictions on day light setting to reduce seabird bycatch could be lifted, which could provide an operational advantage to fishermen and also potentially a significant indirect economic advantage by enabling a more efficient overall operation.

Uptake of the Hookpod, and battery-powered lights more generally, in pelagic longline fisheries would also assist in reducing the marine debris caused by the at-sea disposal of single-use chemical light sticks, which has been identified as a significant source of chemical and plastic pollution in the world's oceans (Pinho, Ihara & Fillmann, 2009).

There has long been a desire from the fishing industry and conservationists to find a 'single' mitigation solution for seabird bycatch in pelagic longline fisheries that is operationally simple to use and cost effective. We demonstrated that the Hookpod is highly effective at reducing seabird bycatch without negatively impacting target catch rates and has potential for reducing bycatch rates on other threatened species (e.g. marine turtles). With widespread uptake in coastal and high seas pelagic longline fleets, the Hookpod could make an important contribution to halting the decline of albatross and petrel populations.

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Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Figure S1. Catch per unit effort of target species [(a) Tuna, (b) Swordfish, (c) Sharks and (d) Other] for each trip within each of the three regions (South Africa, Brazil and Australia), for each treatment type (grey – Hookpod branchlines; white-control branchlines). Note, *y*-axis range varies to enhance readability.