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Setting baited hooks by stealth (underwater) can prevent the incidental mortality of albatrosses and petrels in pelagic longline fisheries

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ABSTRACT

For many decades pelagic longline fisheries have been responsible for the deaths of large numbers of seabirds worldwide. Baited hooks deployed onto the sea surface attract seabirds to fishing vessels leading to attacks on baits, capture and death by drowning. An alternative is to deploy baits underwater where they are less detectable, more difficult to reach and less likely to be taken by seabirds. In 2010 and 2012 proof-of-concept experiments were conducted in the Uruguayan pelagic longline fishery with a newly developed device designed to set baits underwater. The experiments examined the differences between setting baits at the sea surface and setting baits underwater with regard to the abundances of seabirds following the vessel, incidences of attacks on baits and mortality. Underwater setting led to marked reductions in the numbers of seabirds following the fishing vessel and attacks on baits, the behavioural precursors to mortality. Mortality rates of seabirds on baits set to the relatively shallow depth of 4 m were 87% lower than on baits set at the surface. No seabirds were caught on baits released 10 m underwater, a reduction of 100% compared to the surface setting mortality of 11.6 birds/1000 hooks. No differences were detected between the two setting methods in the catch rates of target and non-target fish species. The evidence from the experiments, combined with the known dive depths of the white-chinned petrel (*Procellaria aequinoctialis*), a deep diving, difficult-to-deter species, suggests that baits released 10 m underwater could reduce the incidental mortality of albatrosses and petrels to negligible levels.

1. Introduction

Incidental mortality in commercial longline fisheries threatens the continued existence of seabird populations in many regions of the world and is a key reason why 15 of the 22 species of albatrosses are listed as 'threatened' by the International Union for Conservation of Nature (IUCN, 2017). The commercial longline fisheries with the greatest impact on seabirds are demersal fisheries, which target fish species at or near the seabed, and pelagic fisheries, which target species closer to the surface. In both types of fisheries seabirds die when they attack baited hooks during setting operations, become hooked or ensnared, drawn underwater and drown. The worst affected are the albatrosses and petrels due to their life history strategies (e.g., delayed maturity, low fecundity) which makes them sensitive to high levels of mortality. They are also habitual ship followers, attracted by the availability of baits at or near the sea surface when lines are set. This type of mortality has driven population decreases at some breeding sites over decadal time scales (Anderson et al., 2011). For example, at South Georgia, a probable worst case location in the Southern Ocean, numbers of wandering (*Diomedea exulans*), black-browed (*Thalassarche melanophris*) and grey-headed (*T. chrysostoma*) albatrosses have been decreasing since the mid-1970s and bycatch in fisheries is considered the most likely reason (Croxall et al., 1997; Poncet et al., 2006; Poncet et al., 2017). The decreases continue despite mortality in the local demersal Patagonian toothfish (*Dissosticus eleginoides*) longline fishery falling from high levels in the late 1990s to near zero levels in the early 2000s following the introduction of effective management actions (SC-CCAMLR, 2006; Croxall, 2008). That the negative trends show no signs of abating suggests that pelagic longline (and trawl) fisheries contribute to population decreases. Pelagic longline fisheries target tunas (*Thunnus* spp.) and swordfish (*Xiphias gladius*) in coastal waters and on the high seas and overlap extensively with longline-vulnerable seabirds wherever they range. For many decades pelagic longline fisheries have resulted in the incidental capture and death of large numbers of seabirds

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(e.g., Brothers, 1991; Murray et al., 1993; Baker and Wise, 2005; Jiménez et al., 2010) and effective management responses have proven more difficult to implement than for demersal longline fisheries.

In pelagic longline fisheries baited hooks are set by hand onto the sea surface where they float momentarily before sinking to fishing depths of ~40–200 m depending on species targeted. Setting baits in this manner attracts seabirds to fishing vessels and increases the likelihood they will attack baits as a source of food. This inevitably leads to fatalities and, potentially, reduced fishing efficiency if baits are removed from hooks. Measures to prevent or minimise the number of attacks on baits include the setting of lines at night, use of effective bird scaring streamer lines and adding weights to branch lines to expedite sink rates. Used in concert and in accordance with prescribed performance standards, these measures are effective in deterring seabirds (e.g., Melvin et al., 2014). Together they are considered 'best practice' by the Agreement on the Conservation of Albatrosses and Petrels (ACAP). Two recently developed devices that temporarily disarm hooks while sinking in seabird dive depths (see Baker et al., submitted; Sullivan et al., 2017) are also effective in reducing interactions and are also considered best practice mitigation by ACAP (ACAP, 2016).

All measures described above apply to gear set by hand onto the sea surface, the conventional method of setting. However, with the possible exception of setting at night on the new moon when the absence of illumination makes baits difficult to detect, gear set in this manner must contend with potentially large numbers of seabirds seeking to attack baits. A more effective method might be to set baits underwater unseen by seabirds. This method of setting has two potential advantages. First, it could remove the incentive for seabirds to follow fishing vessels. If ship following ceased fewer baits will be attacked and few, if any, seabirds will be hooked and drowned. Second, with any residual ship following the appropriate response would be to set baits to depths that exceed the known dive limits of attendant seabirds, thereby preventing their mortality.

Here we present the results of research on a newly developed underwater bait setting device designed to prevent seabird mortality without negatively affecting fish catch, while allowing fisheries to operate without the use of other seabird deterrent devices and practices (e.g., bird scaring streamer lines, night setting) or concern of temporal or spatial restrictions to protect seabirds. The research was based on proof-of-concept experiments which examined differences between baits set at the sea surface and baits set underwater with regard to: i) seabird abundances behind vessels (ship following); ii) attack rates on baits; iii) seabird mortality, and iv) fish catch. The experiments were complemented by operational trials (conducted following completion of the experiments) to perfect various design aspects of the new technology of fundamental importance to the capacity to deter seabirds while maintaining fish catch rates.

2. Methods

2.1. Underwater setter concept

The idea to develop a system to mechanically deploy baited hooks underwater as a seabird conservation tool originated from the New Zealand pelagic longline fishing industry and was brought to fruition by Amerro Engineering, Queensland, Australia (www.amerro.com.au). The developmental stages of the device, called the underwater bait setting capsule (hereafter the 'underwater setter'), can be seen at www.underwaterbaitsetter.com.au. The underwater setter is described in detail by Robertson et al. (2015) and shown conceptually in Fig. 1. Briefly, the underwater setter is a computer operated and hydraulically powered machine that deploys baited hooks individually underwater in a capsule. It comprises two hydraulic motors, the 'pull down' motor and 'recovery' motor, each connected to winches equipped with Spectra® rope. One length of Spectra connects the winch on the pull down motor to a capsule docking unit on a removable track assembly fitted to the vessel's transom. The other length of Spectra connects the recovery motor winch to the capsule. During setting, the pull down motor powers the capsule to the bottom of the track (1.5 m underwater) where it is catapulted to target depth, at which point the recovery motor automatically engages and returns the capsule to the vessel. The baited hook is released from the capsule the moment the capsule recovery process commences. The capsule travels down the track assembly on the vessel at 6 m/s, underwater to target depth at ≥3 m/s, and returns to the vessel at 6 m/s; these speeds ensure cycle times (time from beginning to end of a complete cycle) conform to the time constraints of line setting operations. Baits can be conveniently deployed to a predetermined depth using the systems control unit in the wheelhouse. The decision on setting depth will be influenced by the dive capabilities of seabirds attending vessels on any given day, but generally the 5–10 m range is considered sufficient to prevent most or all interactions while being practical for fishing operations. The underwater setter is operated by a single crew member.

2.2. Operational trials

The underwater setter models used in the proof-of-concept experiments were prototypes and not the finished product. Subsequent to the seabird deterrent experiments described below various design aspects of the underwater setter underwent further research and development with each improvement rigorously field-tested. Of particular concern was the capacity of the capsule to i) retain all baits (no drop-outs) between the surface and target depth, and ii) prevent baits from being drawn up the water column once released from the capsule at target depths. These technical issues were resolved and a remodeled capsule produced, which was trialed operationally in 2014 (Robertson et al., 2015), with further refinements tested in 2016 (G. Robertson, P. Ashworth and S. Candy, unpublished data). As with all trials of new design features of the capsule, bait retention on hooks following the underwater release from the capsule was assessed. The methodologies adopted in 2016 were the same as in previous trials (Robertson et al., 2015). The acceptance standards were 100% bait retention in the capsule during descents, ascents of no > 0.5 m upon release from the capsule and 100% bait retention on hooks following release from the capsule.

2.3. Experiments - seabird deterrence and fish catch

2.3.1. Fishing vessel and gear

The seabird deterrence and fish catch experiments were conducted in the Uruguayan fishing zone in the winter months of 2010 and 2012. Uruguay was the preferred location because of historically high abundances of longline-vulnerable seabirds (Jiménez et al., 2011), most notably black-browed albatrosses and white-chinned petrels (*Procellaria aequinoctialis)*. These species are very abundant and among the most difficult to deter; they are two of the commonest species killed in pelagic longline fisheries in the Southern Hemisphere. The experiments were conducted on the F/V *Qian Lian 2*, a 26.5 m long steel longliner rigged to catch swordfish and tunas. The *Qian Lian 2* deployed a 3.5 mm monofilament mainline with 2.0 mm diameter monofilament branch lines attached at 45 m intervals. Branch lines were 14 m long and 20 m long in 2010 and 2012, respectively, and were fitted with 9/0 J-type swordfish hooks and a 75 g lead sinker 4.5 m from the hooks. The mainline was set off the drum over the center line of the vessel in the 'surface set tight' configuration (see Robertson et al., 2010); by this configuration the mainline is set fairly tight, entering the water about 30 m astern. In the surface setting part of the experiments baited hooks were set onto the sea surface to the outer edge of the vessel wake zone at 10–12 s intervals. Individually numbered radio beacons were attached to the mainline at 35-min intervals and floats (six in total) on 15 m droppers were spaced evenly between radio beacons. Vessel setting speed was 9 kn (4.6 m/s). Baits were squid (*Illex argentinus*) and

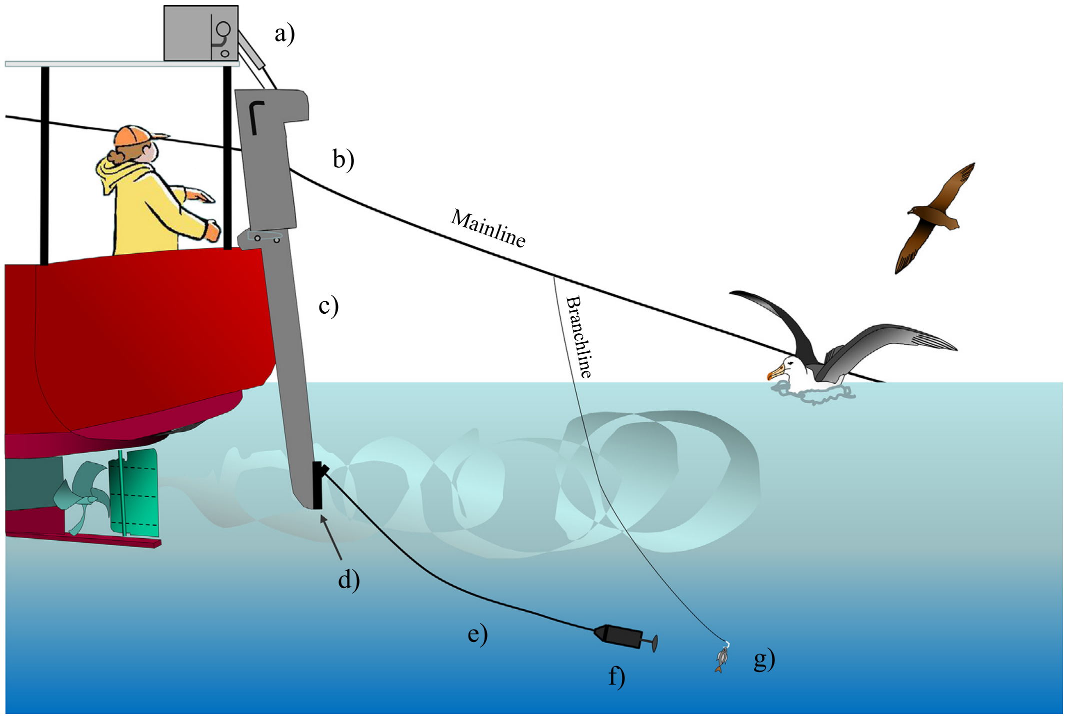

Fig. 1. Schematic showing the main components of the underwater bait setting capsule. Not shown are the systems control units in the wheelhouse and on the back deck. Modified slightly from Robertson et al. (2015).
a) Winch assembly unit – comprises hydraulic motors, winches, Spectra rope and electronics; b) Head section of track assembly – maintains the bait capsule in position prior to bait loading and deployment. Folds inboard when not in use; c) Track assembly – guides the capsule (and capsule docking cart) to bottom of the track where it is hydraulically catapulted to target depth. Raised from water when not in use; d) Capsule docking cart – holds capsule in position on the track; e) Spectra rope - connects capsule to winch assembly unit; f) Bait holding capsule – shown with bait release door extended; g) Baited hook released from the capsule.

mackerel (*Scomber* spp., *Trachurus* spp.) ranging in length from 20 to 35 cm. The *Qian Lian 2* was production fishing during the experiments. Line setting occurred during the day and at night as determined by the fishing operation in seas with a rise and fall of 0.5–2.5 m. A bird scaring streamer line was not deployed with either setting method (the intention was for underwater setting to be a stand-alone seabird deterrent measure).

2.3.2. Underwater setter models

As mentioned, the underwater setter models used in 2010 and 2012 were prototypes. Although some design features required later improvement, of critical importance to the study was that both models were capable of setting baits several meters underwater. The actual depths reached varied as a function of the length of Spectra payed out. In 2010 the length of Spectra was not calibrated for the fast (9 kn) vessel forward speed; this limited the depth that could be practically attained to 4 m. This design feature was rectified in the prototype used in 2012, allowing depths to 10 m to be reached. In both years the bait release depths mentioned below were derived from sea trials before the experiments, using fine scale (10 records/s) time-depth recorders (TDRs; Robertson et al., 2015) in seas with a rise and fall of < 1.5 m (in both years). In 2010 the capsule was the natural colour of stainless steel and the Spectra was red, while in 2012 all external surfaces of the capsule were powder coated matt black and the Spectra was black, to make it more difficult to see when viewed from above which was more in keeping with the idea of setting by stealth.

2.3.3. Experimental design

In 2010 the experiment was conducted over three fishing trips from 17 September and 14 October and involved 15 sets of the longline. In 2012 the longline was set five times on a single fishing trip from 19 to 24 July. The underwater setters used in both years were operated by vessel crew members. The experiments coincided with the non-breeding (winter/early spring) period for black-browed albatrosses and white-chinned petrels and most other species of seabirds on the fishing grounds.

The experimental design was the same in both years. The longline was set once each day with each set comprising gear set by hand at the surface and gear set underwater with the underwater setter. The sample unit was the number of hooks, nominally 164, between consecutive numbered radio beacons. In some sets fewer hooks were deployed due to gear tangles in setting bins, which affected both setting methods, and hook-ups in the prototype capsules. The setting methods were alternated with each successive radio beacon, about every 35 min, giving seabirds sufficient time to respond to the change in setting methods. Alternating the setting methods relatively quickly enabled the sample units to be treated as ‘pairs’, with each member of a pair comprising 164 hooks. This eliminated the confounding effect of ‘set’ (or day, since there was only one set per day). The order of setting method for each new set was randomized to avoid any bias associated with the order of setting. The primary response variables were the number of seabirds killed and the number of fish caught, and the secondary variables were the abundances of seabirds behind vessels during setting operations and the number of attacks on baits of each setting method.

In 2010, baits were released 4 m underwater and beneath the zone of aerated water thrust from the propeller, which to some degree masks the sinking baits for a distance astern. In 2012, baits were set 6 m and 10 m underwater. By this approach only one factor – bait release depth – was varied. The bait release depths were 0 m (hand set at the surface) and 4 m, 6 m and 10 m (underwater setter, all). The dive depth characteristics of black-browed albatrosses and white-chinned petrels (Fig. 2), combined with the necessity to maintain capsule cycle times that were practical for the fishing operation, informed the choice of the three bait release depths.

Fig. 2. Known dive depth characteristics of black-browed albatrosses and white-chinned petrels (Prince et al., 1994, both species) in relation to bait release depths in the experiments (dashed lines). Dive characteristics of grey-headed albatrosses (Huin and Prince, 1997) and shy albatrosses (*T. cauta*) (Hedd et al., 1997) are included for comparison. Shown are average depths, maximum depths, depths reached on the majority of dives and the proportion of dives falling into the latter two categories.

2.3.4. Estimating seabird abundance and attacks

During daylight sets the numbers of seabirds following the vessel were counted for about 30 s to provide an estimate of abundance. The counts commenced 15 min after the start of the set of each member of a pair, which gave seabirds time to respond to the repeated changes in setting methods. Counts were made in an area 100 m astern and 25 m either side of the vessel. Use of visual aids (e.g., floating lines and floats) to delineate the count area was not practical because they may have interfered with line setting and affected the behavior of seabirds following the vessel. The count area was estimated by eye and by one person (GR) only, to maintain consistency. The count area was considered the 'risk zone' (hereafter the expression 'ship following' pertains to seabirds in the risk zone, not those several hundred meters astern). All seabirds that flew through this area or were active in it were counted. The number of attacks on baits was also estimated in daytime sets. The number of attacks was estimated in an area 10 m either side of the bait landing positions (for surface setting) and in the general area of the underwater position of the capsule (aligned with the position of the underwater setter on vessel stern) up to 100 m astern. The distance astern was approximated using the 45 m interval between branch lines as a guide. Attacks were grouped as dives, which were mainly by white-chinned petrels and great shearwaters (*Ardenna gravis*), and deliberate lunges at baits at the surface or duck-dives over sinking baits (mainly albatrosses). For the purpose of comparison of the two setting methods all attacks, including multiple attempts at the same baits (see Jiménez et al., 2012), were grouped as total attacks.

2.3.5. Estimating seabird mortality and fish catch

All target and non-target species landed in hauling operations were recorded by setting method. The numbered radio beacons enabled landed taxa to be apportioned correctly to setting regime. The response variable for all taxa was the number landed on deck.

2.4. Statistical methods - seabird and fish catch experiments

The comparison of surface setting and underwater setting concerning seabird mortality for the 2012 study and the 10 m depth setting did not warrant statistical analysis since all replicate pairs for underwater setting gave zero mortality. In this case even the most rigorous statistical analyses, such as zero-inflated Poisson or negative binomial models (Welsh et al., 1996), become invalid due to the lack of stochastic variation in the response for that treatment. Data for the 6 m depth setting (two seabird captures, see below) were also not analysed because the sample size (< 1000 hooks) was too small to justify analysis. Therefore, only the raw scores for 2012 are presented. For the 2010 study a zero-inflated Poisson (ZIP) generalized linear mixed model (GLMM) (Bolker et al., 2009) was fitted using Markov Chain Monte Carlo (MCMC) estimation as implemented in R (R Core Team, 2013) in the MCMCglmm function within the library of the same name (Hadfield, 2010). The response variable of total seabirds caught (i.e. total across all species by setting method within each pair) in 2010 was modeled with a Poisson error distribution combined with a model component for zero-inflation (relative to a Poisson) (Hadfield, 2014) and the log of number of hooks within each setting method within each pair as an offset (ie. predictions standardized to be rates per 1000 hooks). The linear predictor included the main effect factor of setting method (Method) (i.e. surface set versus underwater set). The offset of log of number of hooks was included in MCMCglmm as an attribute of the Poisson latent component (denoted as the "trait", Hadfield, 2014) by setting the regression parameter associated with the variable of log of the number of hooks with prior Gaussian distribution with mean of 1.0 combined with an extremely high precision (i.e. variance of 10^{-9}). Other parameters were given diffuse priors (Hadfield, 2010). A main effect of day versus night was not included because data from day sets were too few to justify this comparison (see below).

Data for the abundance and number of attacks were totalled across species by setting method within each pair and a GLMM with Poisson response but with no offset (i.e. unlike the number of seabirds caught these estimates were not modeled as rates) was fitted using glmer (Bates et al., 2014) function in the lme4 library in R. The linear predictor included the main effect factor of setting method and also included random effects of pair within fishing trip within set. The number of zeros was not excessive so a zero-inflation component was not added to the Poisson model as was described above for mortality. In 2010 the numbers of hooks set for each pair within trip by setting method for the assessment of attacks (daylight sets only) were consistently close to the nominal 164 hooks with the minimum being 156 hooks. Thus the number of hooks set was not considered as a covariate in the analysis of the attack data.

For fish catch, to compare the effects of baits set underwater with baits set at the sea surface, data for the three underwater setter depths (4 m, 6 m and 10 m) were combined. Unlike seabirds that are caught at or near the surface when lines are set, fish are caught during the soak period, which might last 12 h or more. The differences in time taken for baits set at the surface and the three depths underwater to reach fishing depth was < 30 s, a trivial length of time compared to the length of the soak. Because there were too few individuals of some species to justify analysis, catch data were grouped by taxa or taxa groups: i) swordfish, ii) yellowfin tuna (*Thunnus albacares*), iii) albacore tuna (*T. alalunga*), iv) blue sharks (*Prionacea glauca*), v) commercial species separate from the above; and vi) non-commercial species. The response variables were modeled with a GLMM with a Poisson error distribution and the log of number of hooks within each setting method within each pair as an offset using glmer. The extra component in the linear predictor compared to that above was a main effect of year (i.e. 2010 versus 2012). Random effects of pair within fishing trip within set were also included in the linear predictor. For the yellowfin tuna catches, a zero-inflation component was added in the same way as that for seabird mortality using MCMCglmm because of the excessive number of zero catches of this species relative to a Poisson.

The output of primary interest for each of fish catch rate, total bird catch rates (standardized to number per 1000 hooks), seabird abundance and numbers of attacks (totaled across species) on gear set at the surface compared to gear set underwater, was a single parameter of the percent reduction in catch rate or numbers (abundance and attacks) by underwater setting compared to surface setting deployments (R) (i.e.

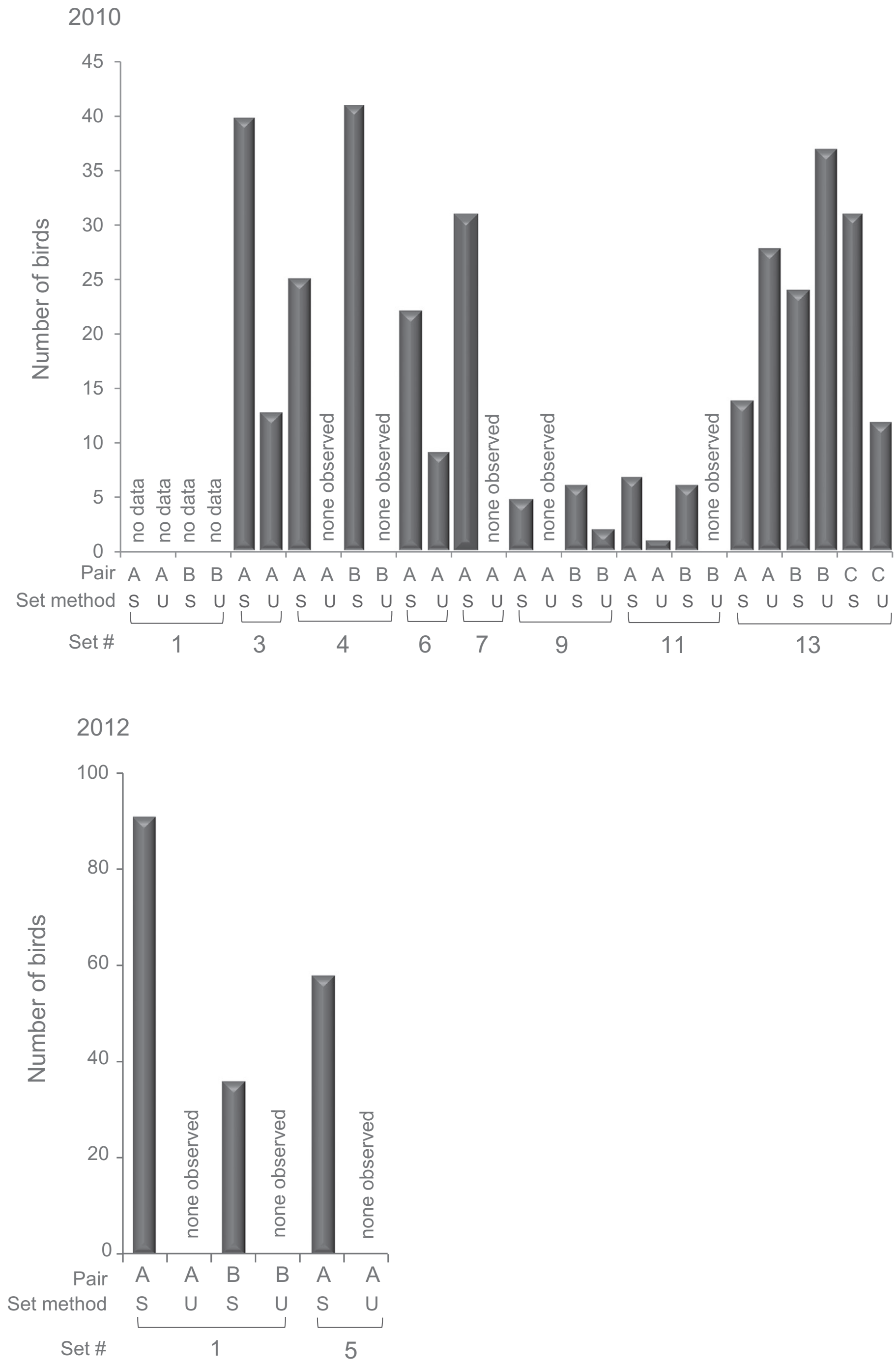

Fig. 3. Estimated abundances of seabirds in the risk zone behind the vessel (see text) in response to baits set at the sea surface compared to baits set underwater. Data are presented as matched pairs within sets of the longline. Missing set numbers indicate either the absence of observations (set 1 in 2010) or sets made at night when observations were not possible (all other missing set numbers). Set method: S = surface set (by hand); U = underwater set (underwater setter). Underwater setter depths were 4 m in 2010 and 10 m in 2012.

this definition does not preclude an increase in catch rate in which case this parameter would have a negative estimate). For the glmer output, using the parameter defining catch rate on the log scale for underwater set minus that for the surface set of $\hat{\tau}$, then $\hat{R} = 100\ [1 - \exp.\ \{\hat{\tau}\}]$, the fixed effect parameter "Method" is equivalent to $\hat{\tau}$. Approximate 95% confidence intervals were obtained for using glmer with lower limit of $100\ (1 – \exp\ \{\hat{\tau} + 2se\ (\hat{\tau})\}$ and upper limit of $100\ (1 - \exp\ \{\hat{\tau} - 2se(\hat{\tau})\}$. This method was also applied to the data on seabird abundance and the number of attacks on baits. By ignoring the year effect for the fish catch responses the estimates were standardized to 2010 rates. For the MCMCglmm output, based on 2000 retained MCMC samples (i.e. "burn-in" sample of 2×10^5 and thinning rate of 1 in 250), the corresponding percent reduction (R) and its 96% support intervals were calculated using catch rates for each method and using the formula for calculating R directly [i.e. $100 \times (\text{Rate}_{\text{surface set}} - \text{Rate}_{\text{underwater set}})/\text{Rate}_{\text{surface set}}$].

The catch rate data were also analysed as presence/absence data with a single value of either a presence or absence for each pair within trip and setting method (i.e. determined across all hooks within a sample unit). Therefore if any number of a species or species group were caught within this sampling unit it was denoted a presence (or an absence if none were caught) and considered to be distributed as a Bernoulli which can be considered as a special case of the binomial with sample size of 1. A binomial/logistic GLMM was fitted to this data using the same fixed and random terms as the Poisson GLMM using the MCMC estimation implemented in MCMCglmm, again with diffuse priors. Since the number of hooks per sampling unit was sometimes substantially below the target of 164 hooks, it could be expected that the probability of a presence for a taxa would increase with number of hooks. Therefore, an extra covariate defined as the number of hooks in the sample unit divided by 164 was added to the linear predictor to adjust for sampling effort (Lecomte et al., 2013). Again, the estimates of proportion of zero catches (i.e. 1 minus the predicted probability of a non-zero catch) were standardized to 2010 catches when data from both years were modeled.

3. Results

3.1. Operational trials

The trialing of the at-sea functionality of re-modeled versions of the capsule that followed the experiments in Uruguay found that the capsule performed to the expected standards regarding bait retention on descents, bait release at target depths and bait retention on hooks post-release from the capsule (Appendix A).

3.2. Experiments - seabird deterrence and fish catch

The experiments comprised 15 sets of the longline in 2010 and five sets in 2012 for a combined total of 18,478 hooks for the study. Of these, 14,720 hooks and 3758 hooks were set in 2010 and 2012, respectively. Of the 18,478 hooks set in the study 9498 were set at the sea surface and 8980 were set underwater. A total of 49 matched pairs (98 sampling units, since there were two sampling units per pair) and 17 matched pairs were set in 2010 and 2012, respectively. In 2010 the nominal sampling unit of 164 hooks was attained for 38 of the 98 sampling units for surface setting and 14 sampling units for underwater setting. With the remainder of the sampling units the mean number of hooks were 103.8 (minimum: 82) and 144.3 (78) for surface setting and underwater setting, respectively. In 2012, the maximum number of hooks set per sampling unit in the 17 matched pairs was 150 and the mean numbers were 124.9 (minimum: 99) and 96.1 (49) for surface and underwater setting, respectively.

In 2010, estimates of seabird abundances and attacks were available for 12 pairs and 14 pairs (daylight sets only), respectively, of the 49 matched pairs set in that year (abundance data for two pairs were not collected for the first set due to time constraints). In 2012, estimates of abundances and attacks were available for only three of the 17 matched pairs. The remaining pairs (86% in 2010 and 82% in 2012) were set at night. Estimates of seabird mortality and fish catch were available for all 49 matched pairs set in 2010 and all 17 matched pairs set in 2012.

3.2.1. Seabird abundance and attacks

In 2010, of the seven daylight sets (or portions of sets), a combined total of 252 birds were observed in the risk zone when baits were set at the surface and 101 birds when baits were set underwater, giving a reduction of 59.9% ($CL_{95\%}$: 49.3 to 68.3%; $P < 0.001$) in favour of underwater setting (Fig. 3). In 2012, of the estimates were 185 birds for surface setting and no birds for underwater setting (10 m depth), a reduction of 100% (Fig. 3). In 2010, a total of 10 species were observed in the risk zone but by far the most abundant were black-browed albatrosses, white-chinned petrels and great shearwaters. In 2012, black-browed albatrosses and white-chinned petrels were the only species observed in the risk zone behind the vessel.

In 2010, there were an estimated 144 attacks on surface set baits and 22 attacks on baits set 4 m underwater, a reduction of 84.7% ($CL_{95\%}$: 76.0 to 90.3%; $P < 0.001$; Fig. 4). All attacks were by black-browed albatrosses, white-chinned petrels and great shearwaters. In the three pairs assessed in 2012 no attacks were observed on baits set 10 m underwater compared to 215 attacks on baits set at the surface, a difference of 100% (Fig. 4).

3.2.2. Seabird mortality

All hooks landed during hauling operations were observed for the number of seabirds and number of fish caught. For both years combined a total of 25 seabirds were caught on baits set onto the sea surface compared to three seabirds on bait set underwater. Of the 28 seabirds caught in total, 12 were caught in 2010 and 16 in 2012. The species caught on surface set baits in both years were black-browed albatrosses ($n = 14$, 1.47/1000 hooks), white-chinned petrels ($n = 4$; 0.42/1000 hooks), northern royal albatrosses (*D. sandfordi;* $n = 3$) and southern royal albatrosses (*D. epomophora;* $n = 4$) (0.74/1000 hooks for both royal albatross species combined). The combined catch rate for both years for all birds caught on surface set gear was 2.94/1000 hooks ($n = 9498$ hooks).

In 2010, one black-browed albatross was caught on baits set to 4 m depth ($n = 7346$ hooks) compared to 11 seabirds caught on baits set at the surface ($n = 7374$ hooks; Table 1), giving an estimated reduction in mortality of 87.0% ($CL_{95\%}$ reductions: 58% to 99%). Conversely, the proportion of sample units (i.e. method by pair by set combinations) that recorded a zero seabird bycatch showed a significant increase ($P < 0.01$) for baits set underwater (Table 1). With respect to the binomial model of presence/absence of total seabird mortality, the regression coefficient used to adjust for sampling effort (number of hooks) was not significantly different from zero ($P > 0.10$). This was also the case for all taxa modeled, so no further reporting of this adjustment to the binomial model is given.

In 2012, of the 16 birds caught in total two black-browed albatrosses were caught on baits set to 6 m depth ($n = 811$ hooks) paired with baits set at the surface, which resulted in the capture of one white-chinned petrel ($n = 1000$ hooks). The remaining 13 birds were caught on the surface-set member (1124 hooks) of the pairs matched with the baits set 10 m underwater (823 hooks). In spite of the extremely high abundances and large number of attacks on baits in that year (see Figs. 3 and 4), no seabirds were caught on baits deployed 10 m underwater. Mortality rates with surface setting and underwater setting to 10 m depth were 11.6 birds/1000 hooks and no birds respectively, 10 m depth giving a reduction in mortality of 100%.

3.2.3. Fish catch

With one exception there was no statistically detectible difference in the catch rates of fish taxa and taxa groups between baits set at the surface and baits set underwater (Table 1). The exception was the proportion of pairs with zero catch for the non-commercial species group where baits set underwater resulted in a significantly greater number of zero catches. For the mean percentage reduction in catch rate, the estimated lower 95% confidence limit for this species group comes close to indicating significance, and the estimate itself is high at 37.5%.

3.2.4. Turtles

The other bycaught taxa of note were turtles. In both years combined 12 loggerhead turtles (*Caretta caretta*) were caught on surface set baits and 13 on baits set underwater. One olive ridley turtle (*Lepidochelys olivacea*) was caught on underwater set baits and one leatherback turtle (*Dermochelys coriacea*) on surface set baits. Catch rates for all turtles combined were 1.36/1000 hooks on baits set at the surface compared to 1.56/1000 hooks on baits set underwater.

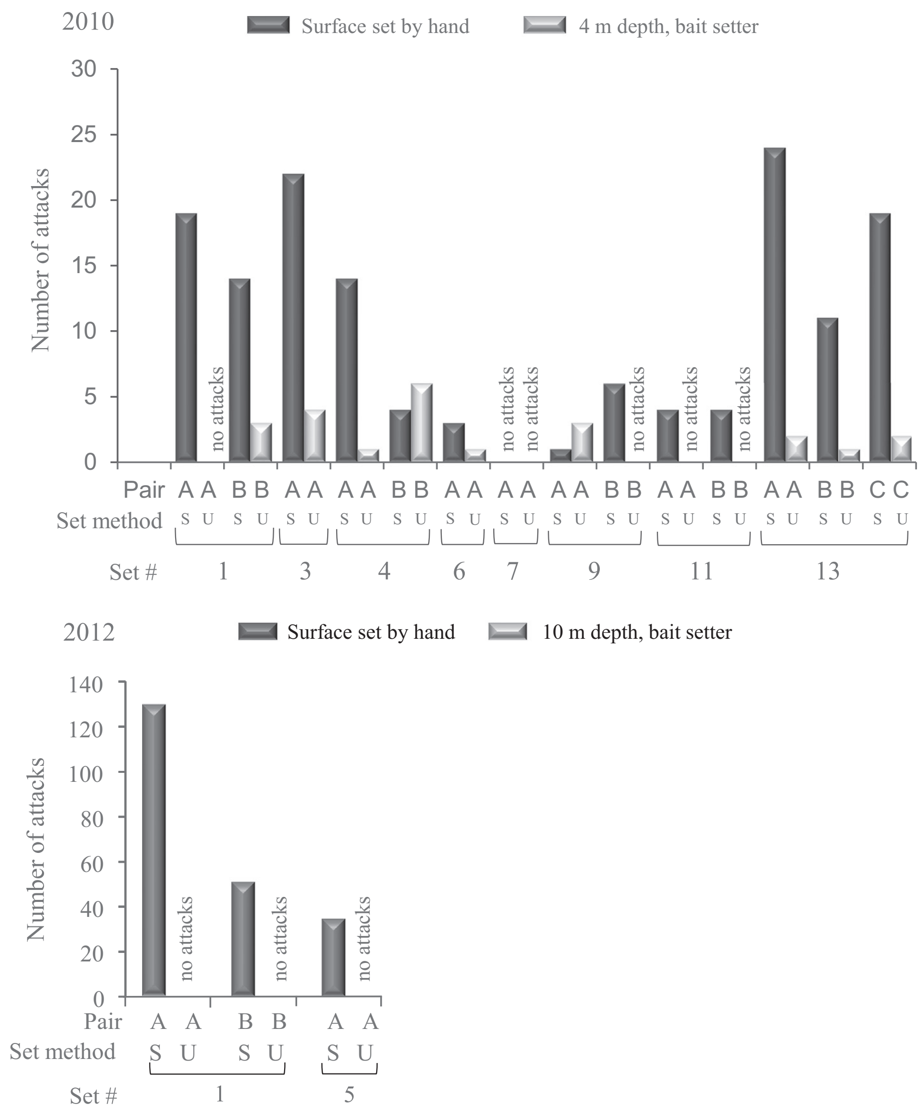

Fig. 4. Estimated number of attacks on baited hooks set at the surface and set underwater in 2010 and 2012. Missing set numbers indicate sets made at night. S = surface set. U = underwater set.

4. Discussion

4.1. Caveat and data limitations

In 2010, a white-chinned petrel was caught on bait set 4 m underwater but was not considered in the assessments. The capture occurred on the second set of the longline and resulted from a small number of baits, improperly loaded and deployed, being pulled from the capsule near the surface. The problem was later rectified, the capsule being redesigned and subjected to rigorous reliability testing in operational trials. If the problem was not rectifiable and remained intrinsic to the underwater setter, then the capture would have been considered legitimate and its omission not justified. Technical improvements since completion of the experiments relevant to bait retention include solid metal covers (instead of the spokes used on the prototypes) over bait loading windows (see Robertson et al., 2015), instant closure on deployment, a mechanical release mechanism for the bait exit door (previously activated by water pressure overcoming the tension of the exit door's spring mechanism) and larger bait holding chambers. As shown in the Appendix these improvements effectively prevent baits from being pulled from the capsule.

The experiment in 2012 was limited to just 17 pairs in five sets of the longline. A mechanical problem emerged on the fifth (and last) set of the longline when large seas combined with the thrust from the propeller and fast setting speed overstressed one of the two hydraulic motors causing it to fail (the problem since rectified). This mechanical failure curtailed the experiment and resulted in much smaller sample sizes than intended.

4.2. Experiments

4.2.1. Seabird abundances and attacks

With one exception, the most prevalent response to the two setting methods was increased abundance with surface setting and decreased abundance with underwater setting. Leaving aside sets when there were very few seabirds in the risk zone, the main exception was set 13 in 2010 (Fig. 3) when great shearwaters were the most abundant species. This species did not exhibit the same pattern of response to the changes in setting methods. Overall, the number of seabirds observed in the risk zone was 59.9% lower with baits set 4 m deep and 100% lower with baits set 10 m underwater. In 2012 (10 m depth) the pattern of attraction followed by avoidance was repeated in each of the three pairs observed. Within a few minutes of switching from surface setting to underwater setting, seabirds vacated the zone behind the vessel to a

Table 1
Mean percent reduction[a] in catch rate and proportion of sets with zero catch[b] for fish taxa for baits set underwater (all depths combined, see text) and seabirds (all species combined) compared to baits set at the sea surface. Values for total seabirds pertain to baits set at 4 m depth only (see text). Positive values for mean percent reduction indicate a reduction in catch by baits set underwater while negative indicate an increased catch rate. Figures in brackets represent lower and upper limits of the 95% confidence limits for the mean estimate. For percent reduction, 95% confidence limits that include zero are not statistically significant. Also shown are mean catch rates and confidence limits for both setting methods. Species in grouped taxa are shown below the table.

Taxa/group	Mean reduction (%)	Mean catch rate/1000 hooks		Prop Zero Catch[b]	
		Surface set (SS)	Underwater set (US)	SS	US
Swordfish	0.82 (−29.16, 23.84)	9.50 (6.59, 13.70)	9.42 (6.54, 13.57)	0.20	0.27
Yellowfin tuna[c]	−9.57 (−118.37, 50.19)	0.78 (0.24, 1.54)	0.80 (0.25, 1.63)	0.91	0.91
Albacore tuna	−3.49 (−32.54, 20.98)	2.72 (1.14, 6.49)	2.82 (1.18, 6.71)	0.66	0.68
Blue shark	5.02 (−5.09, 14.15)	45.89 (30.31, 69.49)	43.59 (28.78, 66.03)	0.03	0.05
Other commercial	−8.81 (−47.42, 19.69)	4.92 (2.75, 8.79)	5.35 (3.00, 9.53)	0.52	0.50
Non-commercial	37.5 (−5.00, 62.79)	1.23 (0.53, 2.82)	0.77 (0.32, 1.83)	0.75	0.92*
Total Birds[c,d]	87.0** (58.0, 99.0)	1.34 (0.60, 2.40)	0.16 (0.01, 0.55)	0.85	0.98*

Other commercial species: big eye tuna (*T. obesus*), southern bluefin tuna (*T. maccoyii*), escalor (*Lepidocybium flavobrunneum*), mahi mahi (*Coryphaena hippurus*), short-finned mako (*Isurus oxyrinchus*), moon fish (*Lampris guttatus*), longbill spearfish (*Tetrapturus pfluegeri*). Non-commercial species: skipjack tuna (*Katsuwonus pelamis*), oil fish (*Ruvettus pretiosus*), ocean sun fish (*Mola spp.*), pelagic stingray (*Pteroplatytrygon violacea*), porbeagle shark (*Lamna nasus*), smooth hammerhead shark (*Sphyrma zygaena*), thresher shark (*Alopias spp.*), snake mackerel (*Gempylus serpens*).

* $P < 0.01$.

** $P < 0.001$.

[a] Estimated percent reduction expressed as 100 x (surface set–underwater set)/surface set based on the fit of the Poisson GLMM. Only species/groups of species with at least 50 individuals represented were analysed (see text).

[b] Estimated mean proportion of pairs within setting method that recorded a zero catch and showing which were statistical significant between the underwater set and surface set obtained from the fit of the binomial GLMM using the MCMC estimate.

[c] Estimated values of mean reduction and catch rate using MCMC estimation and a zero-inflated Poisson GLMM for catch numbers.

[d] Estimated values of mean reduction, catch rate, and proportion zero catch for 2010 only.

position several hundred meters astern, only to return within a few minutes of reversion to surface setting.

Baits released 4 m and 10 m underwater reduced the number of attacks by 84.7% and 100%, respectively, compared to baits set at the surface. Although the finding for 10 m depth is based on only three pairs observed, it nonetheless provides a glimpse of possible seabird responses if all baits were set underwater. The attacks on surface set baits were the most intense recorded in the study and by the end of each surface-set member of a pair black-browed albatrosses and white-chinned petrels attended the vessels in large numbers, yet when underwater setting recommenced not a single attack was observed.

This ‘stop-go’ pattern in abundance and attacks was perhaps the most important observation made during the study. The implication is that if ship following ceased attacks would cease and no seabirds would be caught. Also, if all baits were set underwater setting to the shallow depths might be sufficient to prevent (or greatly reduce) ship following and associated mortality. If a degree of ship following persisted the appropriate response would be deep setting. With a maximum dive depth of only 4.5 m black-browed albatrosses cannot reach baits set deep. White-chinned petrels, consummate divers among the petrel species, rarely dive deeper than 10 m (Rollinson et al., 2014). Baits set about 10 m underwater should be unavailable to both species and to other species of seabirds with similar diving capabilities.

4.2.2. Seabird mortality

The experiments demonstrated that there were significant differences in seabird mortality between the two setting methods, and that mortality was greatly reduced when baits were set underwater. This highlights the seabird conservation benefits of setting baited hooks by stealth - in this case underwater. Baits set to the relatively shallow depth of 4 m underwater reduced seabird mortality by 87% compared to baits set at the surface, and baits set to 10 m depth reduced mortality by 100%. The sample sizes involving the 10 m depth setting were small (surface: 1125 hooks; 10 m: 823 hooks) which could raise the possibility that the number of hooks set was insufficient to adequately assess bycatch. That is unlikely, however, because of the extraordinarily high fatality rate (11.6 birds/1000 hooks) on the surface set members of the pairs and the fact the pairs were matched ($n = 9$), giving comparisons that were head-to-head. Considering the absence of attacks for the underwater set members of the three matched pairs set in daylight shown in Fig. 4, it is not surprising that no fatalities were recorded with 10 m depth. Even if there were attacks it is unlikely that seabirds would have been caught. Baits released 10 m underwater are well beyond the dive range of albatrosses and near the extreme end of the dive spectrum for white-chinned petrels. Thus, the findings are probably indicative of what could be expected with baits deployed at 10 m depth.

Of the 17 matched pairs assessed for mortality in 2012 two black-browed albatrosses were caught on baits set 6 m deep. Both captures occurred on set 1 pair C in twilight with insufficient light to observe abundances and attacks. The captures suggest that a depth of 6 m was insufficient to prevent mortality, at least under a setting regime of alternating setting methods, something that would not occur in production fishing operations with an underwater setter in constant use.

Finally, in 2012 seven royal albatrosses were caught on baits set at the surface. In both years the intention was to expose gear to the species most difficult to deter - black-browed albatrosses and white-chinned petrels—not to the great albatrosses. Lacking the maneuverability of the smaller seabird species, royals are reluctant to venture close to vessel sterns and unlikely to be the first in a multi-species mix to seize baits. Being of similar shape and size to wandering albatrosses, which are poor divers (see Prince et al., 1994), royal albatrosses are unlikely to seek baits that cannot be reached close to the surface. The captures of royal albatrosses must have been due to multiple species interactions that resulted in baits becoming available to them at the surface (see Jiménez et al., 2012). The interactions must have occurred far behind the vessel since no royal albatrosses were observed in the risk zone in 2012.

4.2.3. Fish catch

There were no detectible differences in catch rates of the main target fish species and the ‘other commercial’ group of species between baits set at the surface by hand and baits set with the underwater setter. This finding is not surprising given the small differences in bait release depths tested in the experiments (compared to target fishing depths) and the results of the operational trials concerning bait retention on hooks following release from the capsule. With respect to the non-commercial group of species, the paired comparison within setting method demonstrated a significantly ($P < 0.01$) higher proportion of pairs with zero catches for baits set underwater compared to baits set at the surface: 0.92 versus 0.75. This finding is unlikely to have resulted from sampling bias because the comparisons were within pairs and the sample size (49 pairs in 2010 and 17 in 2012) was substantial. The non-commercial species are an ecologically disparate group and there is no obvious reason why baits set underwater would yield a higher proportion of zero catches than baits set at the surface.

The great reduction in the number of attacks on baits set underwater could result in improved fish catch, since more baits should be available and undamaged at fishing depth. However, for blue sharks, the species most commonly caught and with the relative catch rate the most precisely estimated, the statistical power was insufficient to detect even a 10% change (Table 1). This does not mean an absence of effect, rather it suggest any improvement in the catch rates of commercially important species could be subtle, requiring a far larger sample size to detect than available in the experiments. Preventing seabirds from contacting baits could be an important point in favour of underwater setting since even a modest increase in catch requiring, say, an entire fishing year to detect, could result in considerable economic benefit if the increase pertained to fish species of high commercial value (e.g., tunas).

4.2.4. Turtles

In both years combined the bycatch of loggerhead turtles was similar for both setting methods. Baits released at the surface and at the three depths underwater all reached fishing depth within about 30 s of one another, a time span dwarfed by the 12 h or so baits spent at fishing depth during the soak. Turtles generally get hooked underwater so it is unsurprising that no difference was found between setting methods in the bycatch of loggerhead turtles.

4.3. Experiments versus production fishing

The findings from the experiments are not necessarily indicative of what could be expected in production fishing operations with an underwater setter in constant use. Some seabird species (e.g., white-chinned petrels) are persistent followers of fishing vessels and the short time period (c. 35 min) allotted to each setting method in the experiments may have inflated the number of seabirds in attendance on transitions from surface setting to underwater setting. Judging by the contrasting behavioural responses to the two setting methods, most evident for 10 m depth but also for the shallower depth of 4 m, if all hooks were set underwater it is conceivable that few, if any, seabirds would frequent the risk zone behind the vessel. In that event there would be few, if any, attacks on baits and few, if any, fatalities. Whether these predictions are realistic or seabird behavioural responses more nuanced in the absence of baits at the surface will be revealed when underwater setting is adopted (and conducted for an appropriate length of time) in production fishing operations.

4.4. Benefits of line weighting

Although both weighted and unweighted branch lines can be set with the underwater setter there are certain operational and seabird conservation related benefits with the use of weighted branch lines. For example, at a vessel speed of 6 kn (3.1 m/s) the capsule (sink rate: c. 3 m/s) will reach 10 m depth about 11 m astern beneath water aerated by propeller turbulence. Assuming a delay of three seconds before diving and a dive rate of 1.5 m/s (Rollinson et al., 2014), a white-chinned petrel would reach 10 m depth in about 10 s (ie. $10\ \text{m} \div 1.5\ \text{m/s} + 3\ \text{s}$). In that time baits on branch lines configured with 60 g at 3.5 m from the hook (average sink rate post release from the capsule: 0.41 m/s (Robertson et al., 2015)) would be 14 m deep—and sinking (i.e., $10\ \text{m} \div 1.5\ \text{m/s} + 3\ \text{s} \times 0.41\ \text{m/s} + 10\ \text{m}$). It must be remembered that the majority (95%) of white-chinned dives do not exceed 7 m depth and only 1% reach the maximum of 16 m. This rationale suggests that baits set shallower with faster sink rates post-release from the capsule might be as challenging to reach as baits set deeper but with slower sink rates post release. Operationally, the advantages are faster capsule cycle times, favoured by some fishing operators, and reduced demand on underwater setter hydraulics and vessel power supply.

4.5. Conclusions and next steps

Underwater setting is a new paradigm in fishing with considerable conservation benefits to seabirds. Setting to the relatively shallow depth of 4 m reduced mortality by 87% and setting to 10 m deep reduced mortality by 100%. Underwater setting also led to marked reductions in the number of seabirds following the vessel and fewer attacks on baits, the behavioural precursors to mortality. The effect on the number of seabirds following the vessel was perhaps the most salutary point to emerge from the experiments. If seabirds follow fishing vessels for no other reason than to attack baits, then if all baits were set underwater ship following might reduce even further. The most important next step will be to test this hypothesis in the context of production fishing with all baits set underwater to a range of bait release depths. At the same time, if a degree of ship following and attacks persist, it will be important to quantify any residual mortality associated with the various bait release depths and to determine the depth at which the mortality of seabirds no longer occurs.

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Appendix A. Results of performance tests of the final version of the capsule

Summary of incidences of i) failed bait retention (drop-outs) by the capsule on descents to target depths, ii) baits being drawn up the water column post-release from the capsule (drag-backs) and iii) bait retention on hooks post-release from the capsule. Data expressed as a function of contrasting (fastest, slowest) vessel setting speeds and bait release depths (shallow, deep). Included are data from a single branch line tethered to the vessel and used multiple times (see Robertson et al., 2015) and branch lines set on mainline as in normal fishing operations. 'W' denotes branch lines weighted with a 60 g leaded swivel 3.5 m from hooks. 'UW' denotes unweighted branch lines (no added weight). Total deployments = 906. Sources: a) Robertson et al., 2015; b) G. Robertson, P. Ashworth and S. Candy (unpublished data, 2016).

Deployment method	Weighting	Vessel speed (knots)	Bait release depth (m)	Deployments (*n*)	Drop-outs (*n*)	Drag-backs (*n*)	All bait retained on hooks?	Source
Tethered	W	6	6	100	0	0	y	a
Tethered	W	6	10	100	0	0	y	a
Tethered	W	9	10	50	0	0	y	a
Tethered	W	9	10	50	0	0	y	a
On mainline	W	6	6	38	0	0	y	a
On mainline	W	6	10	115	0	0	y	a
On mainline	W	9	6	38	0	0	y	a
On mainline	W	9	10	115	0	0	y	a
Tethered	W	6	6	50	0	0	y	b
Tethered	W	6	10	100	0	0	y	b
Tethered	W	8	10	50	0	0	y	b
Tethered	W	8	10	50	0	0	y	b
Tethered	UW	6	6	25	0	0	y	b
Tethered	UW	6	10	25	0	0	y	b

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