AQUATIC CONSERVATION: MARINE AND FRESHWATER ECOSYSTEMS
Aquatic Conserv: Mar. Freshw. Ecosyst. **20**: 632–643 (2010)
Published online in Wiley Online Library
(wileyonlinelibrary.com). DOI: 10.1002/aqc.1140

Experimental determinations of factors affecting the sink rates of baited hooks to minimize seabird mortality in pelagic longline fisheries

GRAHAM ROBERTSON*, STEVEN G. CANDY, BARBARA WIENECKE and KIERAN LAWTON
Australian Antarctic Division, Channel Highway, Kingston, Tasmania 7050, Australia

ABSTRACT

1. An experiment was conducted in Australia's pelagic longline fishery to establish a scientific basis for the introduction of line weighting to reduce seabird mortality. The experiment examined the effects of different bait species (blue mackerel, yellow-tail mackerel and squid), bait life status (dead or alive), weight of leaded swivels (60 g, 100 g and 160 g) and leader length (distance between leaded swivel and hooks: 2 m, 3 m and 4 m) on the sink rates of baited hooks from 0–6 m deep.

2. On average, live bait sank much more slowly than dead bait. The sink rates of individual live bait were highly variable: many were <2 m underwater 18 s after deployment, including some on the heaviest swivels, and some were <10 m deep after 120 s.

3. Within the dead bait group, all three swivel weights on 3 m and 4 m leaders sank at similar rates. Initial sink rates (e.g. 0–2 m) were 2–3 times slower than final rates (e.g. 4–6 m) for all combinations of swivel weight and leader length. The fastest initial and final sink rates were associated with heavy swivels placed close to hooks.

4. The results show that (a) compared with dead bait, live bait greatly increases the exposure of baited hooks to seabirds; (b) initial sink rates of dead bait are increased by placing leaded swivels close to hooks and final rates by increasing the weight of the swivels; (c) adding weight to long leaders makes little difference to sink rates; and (d) the small (incremental) changes to swivel weights and leader lengths typically preferred by industry will be difficult to detect at sea and unlikely to substantially reduce seabird mortality.

5. We suggest that experiments designed to reduce seabird mortality from that associated with 60 g swivels and ~ 3.5 m leaders (the preferred option by industry) should aim to expedite the initial sink rates as well as rates to deeper depths. This objective could be achieved by including branch lines with ≥ 120 g swivels ≤ 2 m in comparative assessments of the effectiveness of line weighting regimes in reducing seabird mortality.

Received 12 March 2010; Revised 7 July 2010; Accepted 19 July 2010

KEY WORDS: pelagic longline fisheries; sink rates; line weighting; bait species; bait life status; seabird conservation; cooperative research

INTRODUCTION

Experiments designed to determine the effectiveness of techniques to avoid seabird mortality in longline fisheries usually use the number of seabirds killed as a measure of the effectiveness of each method being tested. It is generally the case that limits are placed on the total number of seabirds to be taken, due to legal requirements (e.g. if seabirds are of uncertain conservation status) or ethical considerations of the researchers and/or authorities granting permits (Agnew *et al.*, 2000; Melvin and Walker, 2008). Limiting total mortality influences the number of factors that can be experimentally assessed, which has implications for sample sizes and statistical power to test hypotheses of no difference between effects. Consequently, seabird avoidance experiments are often designed to test relatively few factors or levels within factors (Agnew *et al.*, 2000; Robertson *et al.*, 2006). A prerequisite for such designs is knowledge that the various factors/levels tested will produce contrasting responses, otherwise large samples sizes will be required, potentially resulting in an unacceptably

*Correspondence to: G. Robertson, Australian Antarctic Division, Channel Highway, Kingston, Tasmania 7050, Australia. E-mail: graham.robertson@aad.gov.au

large number of fatalities. Thus, it is often necessary to precede seabird avoidance experiments by operational, or gear-related, experiments to identify the most important factors to manipulate experimentally against seabirds. This two-stage approach was useful with research on the sink rates of gear with the autoline (Robertson *et al.*, 2006) and Spanish methods (Robertson *et al.*, 2008a) of deep water longlining due to the complex gear designs (especially with the Spanish system) and uncertainty about some of the key determinants of sink rate. The approach is equally relevant to pelagic (surface) longline fisheries because of the number of features that could potentially affect sink rates and therefore the frequency of interactions with seabirds.

This paper describes the results of an experiment to improve understanding of factors affecting the sink rates of baited hooks used in Australia's eastern tuna and billfish longline fishery (ETBF). The main target species in the fishery are yellow-fin tuna (*Thunnus albacares*), big eye tuna (*T. obesus*), southern bluefin tuna (*T. maccoyii*), albacore tuna (*T. alalunga*) and broadbill swordfish (*Xiphias gladius*). A motivation for the research was the large number of seabirds taken in the fishery in the early 2000s, including a number of threatened species (Baker and Wise, 2005), which at the time exceeded the standard permitted by legislation (<0.05 birds/1000 hooks; AAD, 2006). A further motivation was the dearth of studies in the published scientific literature on the relationships between gear configuration and the rate at which baited hooks sink. This relationship is critically important, as is that between sink rates and seabird mortality. Modifying gear to increase sink rates is an effective seabird mitigation measure in demersal longline fisheries (Agnew *et al.*, 2000; Robertson *et al.*, 2006; Dietrich *et al.*, 2008; Moreno *et al.*, 2008) and the same should apply to pelagic longline fisheries. At the time of the experiment unweighted branch lines were widely used in the ETBF as was live bait, which complicated efforts to understand the relationships between gear design and sink rates.

Although the experiment was conducted in Australia the results are relevant to tuna and swordfish fisheries in other countries as most pelagic longline fisheries in the southern hemisphere use similar gear configurations (ACAP, 2007). Pelagic longline fisheries in the southern hemisphere continue to exact a heavy toll on migratory seabirds (Petersen *et al.*, 2008; Bugoni *et al.*, 2008; Waugh *et al.*, 2008; Jimenez *et al.*, 2009). The specific aims of the experiment were to (a) determine the effect of bait species, bait life status, leaded swivel weight and leader length (distance between swivel and hook) on the sink rates of baited hooks, (b) use the results of the experiment as a basis for the introduction of line weighting regimes into the fishery to minimize the take of seabirds, and (c) in the event that seabird mortality exceeded desired target levels following the introduction of line weighting, use the results of the experiment to identify a new regime to test experimentally to further minimize seabird mortality.

METHODS

Characterizing sink profiles/rates

The sink profiles/rates of baited hooks depend on whether branch lines contain added weight, such as leaded swivels, and the proximity of the leaded swivel to the hook. Typically, weighted branch lines sink in two stages (see Results and Robertson *et al.*, 2010). The first stage occurs immediately on deployment and is characterized by relatively slow sink rates. The second stage occurs shortly after deployment and is characterized by a linear (i.e. constant) sink profile – and much faster sink rate – to target depths. The duration of the first stage is influenced primarily by the proximity of the leaded swivel to the baited hook. Leaded swivels sink faster than baited hooks until the line connecting them becomes taut. At this point the sinking swivel engages fully on the baited hook and pulls it down, increasing the sink rate. The sink rate of the second stage is influenced by the weight of the swivel. Baited hooks on branch lines without leaded swivels (or an equivalent point source of weight) do not sink with the same two-stage profile. Instead they sink with a near-linear profile from the surface (Melvin *et al.*, 2009), albeit at a slower rate than weighted gear in the second stage of the sink profile. This same profile would also be expected if weight is placed at the hook.

In this paper the first stage is termed the 'initial' sink rate and the second, the 'final' sink rate. Both stages can be expected to have implications for seabird interactions. The initial rate defines the length of time baited hooks are near the surface and thus most visible and accessible to seabirds, and the final rate has implications for dive depths and swimming speeds required if seabirds are to access baits deeper in the water column. Ideally, the sink rates for both stages should be similar (creating a linear profile from the surface) and as fast as is practicable for fishing operations.

Preliminary research

The research at sea was preceded by two trials conducted under static conditions to determine if the methods used at sea affected the sink rates of baited hooks. The first trial examined the effect of attaching time-depth recorders (TDRs) to branch lines to estimate the sink rates of baited hooks. The second trial determined the effect of light sticks attached to branch lines on sink rates. Light sticks are typically used with squid bait to target broadbill swordfish. The methods used and results of the trials are described in Appendix A.

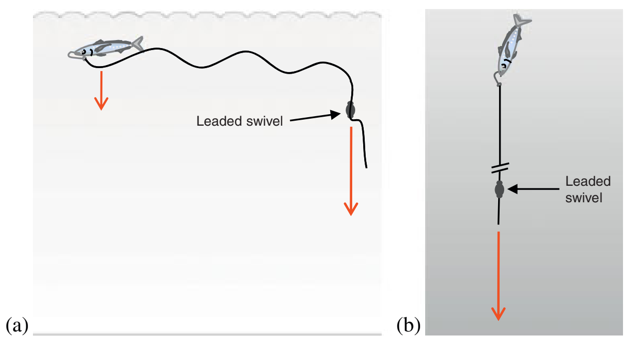

Figure 1. The source of the difference between the initial (part 'a') and final (part 'b') stages of line sinking. Landed baits sink slower than the leaded swivel until the length of line connecting them becomes taut. The initial sink rate is influenced primarily by leader length and the final sink rate is influenced solely by the weight of the swivel.

Line weighting experiment

Fishing vessel, location and gear

The experiment was conducted on the F/V *Assassin*, 12 nm east of Forster (32° 13′S; 152 × 32′E), NSW, Australia, from 15–17 April 2005. The *Assassin* is a 20.7 m long, 40 tonne fibreglass 'Westcoaster' planing hull vessel rigged for stern setting and was chartered specially for the experiment (not fishing commercially). The 3.2 mm diameter monofilament nylon mainline was set over the centre line of a single, four blade, 1.07 m diameter, fixed pitch propeller. The vessel set at 8 knots (4.1 m s^{-1}) and the propeller rotated in a clockwise direction when viewed from a forward facing position. The mainline was set in a 'surface set tight' configuration (see Robertson *et al.,* 2010) through a line shooter running at 4.1 m s^{-1}, identical to the vessel setting speed. Using this configuration the mainline entered the water about 35 m astern with a gentle downward bow, which was typical of surface set tight gear. The relationship between vessel forward speed and line shooter speed was maintained throughout the experiment.

The mainline was suspended in the water by floats on 5 m long droppers. The branch lines were purpose built for the experiment to exact dimensions. Branch lines were 1.8 mm diameter monofilament nylon and were 15 m long from clip to swivel. Leaders were either 2 m, 3 m or 4 m long (see below). Swivel weights were 60 g, 100 g or a combination 160 g (60 g and 100 g swivels crimped together 8 cm apart; 160 g swivels are not commercially available). Baits were attached to ♯3.4 sun tuna hooks weighing 10.4 g. Six branch lines were deployed between each pair of floats and branch lines were deployed ~40 m apart (every 10 s), which was also the distance between the first or last branch lines and the floats (floats were ~300 m apart). Bait species were blue mackerel (*Scomber australasicus*), yellow-tail mackerel (*Trachurus novaezelandiae*) and arrow squid (*Nototodarus gouldi*). Both live and dead fish of both species were used in the experiment. Dead fish of both species and squid baits were procured frozen from the local bait supplier. The average weights and lengths of 10 randomly selected baits of each species were: blue mackerel, 205 ± 18.4 g (s.d.) and 25.2 ± 1.3 cm; yellow-tail mackerel, 110 ± 27.1 g and 20.2 ± 2.2 cm; arrow squid, 293 ± 14.7 g and 23.0 ± 0.5 cm. All dead bait was fully thawed before deployment. A light stick was attached 0.40 m from the hook of all branch lines with squid bait. Live fish bait was hooked through the middle of the back, dead fish bait through the back of the head and squid through the head end of the mantle. The sea state was calm (wave height < 1.0 m) on all days of the experiment and wind was variable to 10 knots.

Experimental design

The experiment examined the effect of bait life status, bait species, leader length and swivel weight on the sink rates of baited hooks (Figure 2). There were two levels within bait life status (live and dead), three levels within bait species (yellow-tail mackerel, blue mackerel and arrow squid), three levels within leader length (2 m, 3 m and 4 m) and three levels within swivel weight (60 g, 100 g and 160 g). This 5 × 3 × 3 design yielded 45 combinations of factors and levels within factors.

In total, 45 branch lines were used on each set of the longline, each with a TDR attached. To minimize/eliminate potential confounding effects associated with 'day' or 'time of day' of setting, all combinations of effects (factors) were completed in each set of the longline. Gear was set systematically (not randomly) to avoid confusion in the deployment procedure and always in the following order: live yellow-tail mackerel, live blue mackerel, dead yellow-tail mackerel, dead blue mackerel and then squid. Within each of these bait life statuses and species, the three leader lengths were deployed in ascending order. Lastly, within each leader length swivel weights were deployed, also in ascending order. Once all 45 branch lines had been set the longline was winched on board and the process repeated. The longline was set a total of 11 times in the three days of the experiment.

The three species of bait and the live and dead forms of fish bait covered virtually all the bait options used in the fishery. The three levels of swivel weights and the three leader lengths were chosen to try to detect trends to inform the decision-making process regarding selection of an appropriate line weighting regime for the fishery. The bait species used were similar in size and weight to those adopted in many other

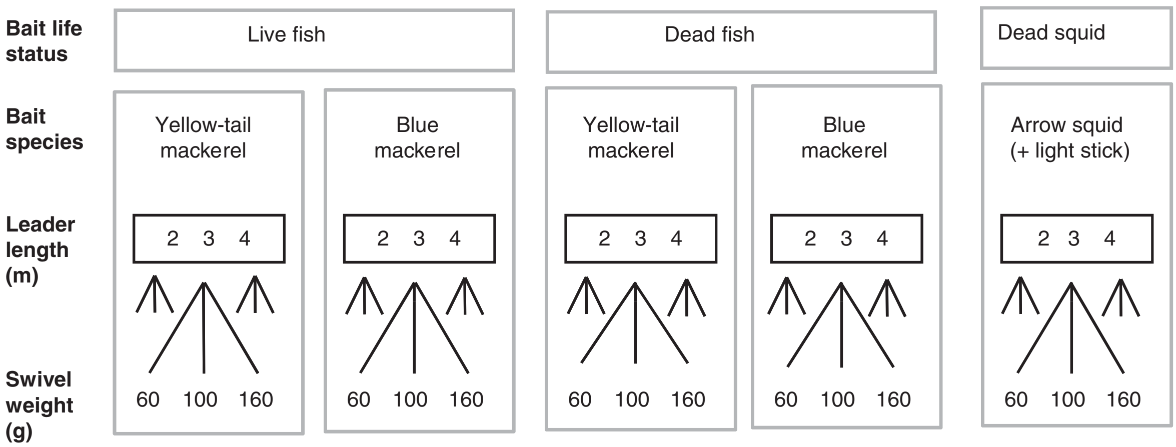

Figure 2. Experimental design showing the hierarchical order of factors testing for the effects of bait life status, bait species, leader lengths and swivel weights on the sink rates of baited hooks. The figure has been simplified for clarity. The boxes around bait species highlight the absence of live squid (no live squid used in the fishery) and the boxes encompassing the leader lengths indicate that within each of the three levels of leader lengths there were three levels of swivel weights.

coastal pelagic longline fisheries in the southern hemisphere, as were the leader lengths (2–4 m commonest; source: ACAP, 2007). The 60 g swivel weight fell within the range for other countries (45–80 g; source: ACAP, 2007) but the 100 g and 160 g swivels were unique to the experiment. In addition to Australia, live fish bait is used in the 'baitboat' fishery for bluefin (*T. thynnus*) and albacore tuna in Spain (Rodriguez-Marin *et al*., 2003), the Brazilian pole-and-line fishery for skipjack tuna (*Katsuwonus pelamis*) and dolphinfish (*Coryphaena hippurus*) (Bugoni *et al.,* 2008) and pole-and-line tuna fisheries operated by Japan and Indonesia (source: Fishing News International, 2009).

Measuring sink rates

Sink rates were recorded with Mk 9 TDRs (Wildlife Computers, USA; 66.5 × 17 mm; 30 g in air) attached to branch lines 0.3 m from hooks with crimps, tape and miniature cable ties. The TDRs were assumed to have had no effect on the final sink rate and a very minor effect on the initial sink rate (Appendix A). TDRs were configured to record depth at 0.5 m increments every second. The water entry times of each TDR were recorded to the nearest second on a digital watch synchronized with the TDR clocks. On retrieval the TDRs were downloaded to computer and the water entry time (from the digital watch) noted in the time–depth files. TDRs usually do not record pressure accurately at the water surface. The error (offset) at the surface was taken to be the median value of the 10 rows of data before the water entry time. This value was used to 'correct' the depth readings of the TDRs.

Line casting procedure

To ensure the mainline was not dragged at the start of each set, which would impede sinking (Robertson *et al.,* 2010), 700 m of mainline and buoys (but not branch lines) were deployed prior to the first hook being set. Similarly, so that the last hook deployed in a set could sink unimpeded by tension on the mainline, the last hook in a set was followed by a further 700 m of mainline and floats. Branch lines were set from separate bins on both sides of the vessel in alternating order. Thus, of the six branch lines deployed between each pair of floats three were deployed to port and three to starboard. The swivel was thrown over the stern and allowed to drag in the water creating resistance, which served to pay out sections of the branch lines from the bins. Hooks were then baited and light sticks attached 0.4 m from hooks (in the case of squid bait). On the cue from an audio beep timer baits were cast into the sea ~1 m astern and in line with vessel gunnels on the outer edge of the wake on both sides of the vessel. The clip end of the branch line was then attached to the mainline without delay.

Data analysis

Sink profiles were analysed for depth to times from water entry until 18 s later, in 1 s intervals. This elapsed time (and associated depth range) was dictated by the cumulative mean sink rate of the fastest sinking combinations (dead bait with 160 g and 2 m leaders) in relation to the 15 m length of the top end sections of the branchlines. Once the top ends of branch lines became taut the sinking baits would drag on the mainline and slow down, thereby preventing valid comparisons with the other combinations. The first ~18 s includes the period when hooks are near the surface and considered most accessible to seabirds, and corresponded to 0–6 m depth of the water column. This depth range provided approximations of both the initial and final phases of sink profiles described earlier, which were taken to be the 0–2 m and the 4–6 m depth ranges, respectively. In addition to the analysis to 18 s, data for live bait (but not dead bait; see below) were assessed up to 120 s after deployment to determine if baits had reached target depths.

The data were analysed using linear mixed models (LMMs) as described in Robertson *et al.* (2008b, 2010). This approach, which models all the data in the 0–6 m range, enables assessment of differences between the various effects throughout the entire sink profiles. The sink rates to target depths (e.g. 0–2 m; 4–6 m) were predicted from the modelled profiles. Using this approach the predictions 'gain strength' because the entire profiles are considered as a sequence of related values, rather than a set of time-specific means to target depths.

Fixed effects in the LMM were bait life status, bait species, leader length and swivel weight. The crew of the *Assassin* deployed branch lines on both sides of the vessel which necessitated the inclusion of side-of-setting (port versus starboard) as an additional factor. Since only dead squid baits were deployed, the interaction of bait life status and bait species has a missing combination. Therefore to test main effects and interactions for these factors, one version of the LMM fitted excluded profiles for squid baits.

The repeated observations of depth (i.e. depth to time profiles) were modelled using LMMs (Diggle *et al.,* 2001) fitted using the *asreml* library (Gilmour *et al.,* 1995, 1999) within the R software package (R Development Core Team, 2006; see Robertson *et al.,* 2008b). Both non-parametric and parametric forms of the LMM were used, the former to model mean values of time to depth for each time point and the latter to fit cubic splines to give smooth curves of depth as a function of time. The random terms in both forms of the LMMs (apart from spline random deviation terms in the parametric LMM) were set number (with nine levels, Table 1) and the profile number (with 127 levels, see below).

To account for increasing variance of depth with time given the treatment combination, data were log transformed so that the response variable fitted by the LMM was $y = \log(\text{Depth}+1)$ and predictions on this scale, $\hat{y}$, could be back-transformed to give a predicted depth of $\exp(\hat{y}) - 1$. The autocorrelation between depths within a profile were modelled using an exponential power model (Gilmour *et al.,* 1995, 1999; see Robertson *et al.,* 2008b). Since there was a strong indication from graphs of profiles of individual branch lines that live baits resulted in more variability than dead baits, an extra variance parameter was incorporated in the LMM to account for this (Appendix B).

Sink rates in the initial 18 s were predicted using the parametric LMM to search across time at 0.1 s intervals for predictions of depth given time that were a close approximation of the nominal depths. The actual predicted depths closest to the nominal depths were then divided by the corresponding time to give sink rates. Incremental sink rates were derived by dividing the difference in consecutive predicted depths by the time taken to sink across consecutive nominal depths (including that for the 0–2 m depth which is equivalent to the cumulative sink rate to 2 m).

Approximate standard errors of predicted depths used to obtain sink rates were $SE(\hat{y})\{\exp(\hat{y})-1\}$ where $SE(\hat{y})$ is the standard error on the transformed scale. The approximate widths of the 95% confidence bounds for the difference between the predicted average depth versus time profile between pairs of treatment levels or pairs of combinations of treatments with one or other of the other fixed effect factors have two values of $2\sqrt{2}SE(\hat{y})\{\exp(\hat{y})-1\}$, since $\hat{y}$ depends on each factor level in the comparison. To allow a visual comparison of these differences a simple method of presenting and interpreting their confidence bounds which overcomes the problem of the width of bounds having two values is described below. The first 2 in the above formula is the 95% probability two-sided t-statistic with 60 degrees of freedom (i.e. nominally there were 54 profiles for each treatment and a minimum of 17 for each combination of treatment and float set or block with corresponding t-statistic of 2.1). The square root of 2 in the above formula is based on the assumption that predicted means have negligible covariance across factor levels for a given time.

Interpreting the confidence bounds

The 95% confidence bounds are shown as pairs of mirror-image lines, one pair for each treatment, along the bottom of Figures 3 and 5 to simplify the presentations. If differences between average sink profiles for a given time exceed the distance between the upper bound of one profile and the lower bound of another in the comparison, then the difference can be considered significant at the 95% level. For example, in Figure 5(a), which shows results for the three leader lengths with 60 g swivels, the distance between the profiles for 2 m leaders and 4 m leaders exceeds the space between the upper confidence bound for the 2 m profile and the lower bound for the 4 m profile. Therefore the difference in sink profiles of these two leader lengths is statistically significant.

RESULTS

Of the 505 depth–time profiles (11 sets with 45 branch lines per set) 485 were retained for analysis. Of the 20 that were rejected, three were rejected due to inaccuracies in recording the water entry times, eight were rejected because of spurious TDR readings and nine were rejected due to slight delays in clipping branch lines to the mainline following bait casting, which may have delayed sinking. The results are presented as comparisons of entire sink profiles (the subject of the LMM analysis) and comparisons of mean sink rates in the initial (0–2) and final (4–6 m) stages of the sink profiles mentioned earlier.

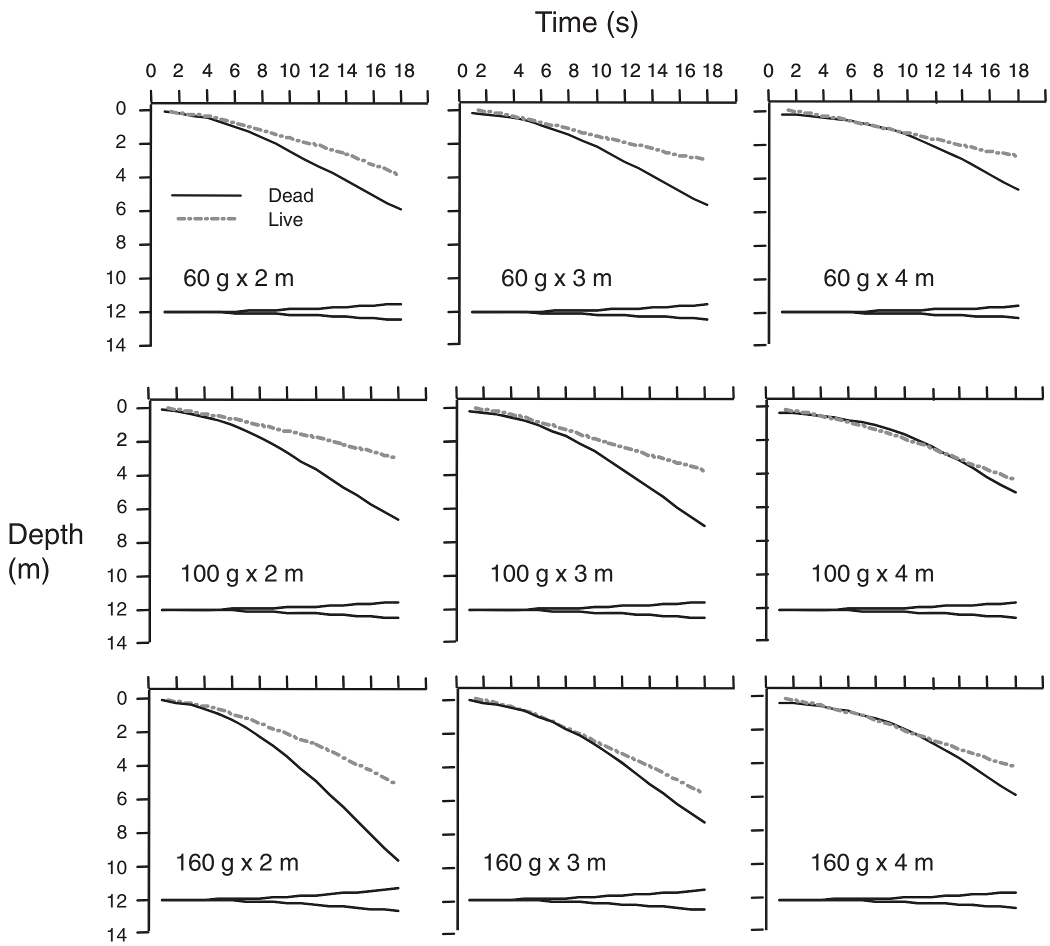

Figure 3. Mean sink profiles of dead and live yellow-tail mackerel and blue mackerel bait in relation to swivel weight and leader lengths in the first 18 s after deployment. Data for both fish species have been averaged (see text and Table 1). See Methods for interpretation of confidence bounds. $n=22$ for each swivel weight $\times$ leader length combination.

Effect of side of setting

Sink rates of gear set on the upswing side and the downswing side of the propeller were not statistically different ($P > 0.1$), so the data for both sides were pooled.

Fish baits: live versus dead

There was no detectible difference in mean sink profiles between yellow-tail mackerel and blue mackerel baits within the same bait life status (Tables 1 and 2). There was a significant interaction between bait life status and leader length (Table 1). The source of the interaction is the contrast between the sink profiles of the 4 m leader and those for the 2 m and 3 m leaders (Figure 3). Dead fish baits on 2 m and 3 m leaders sank considerably faster than their live counterparts irrespective of swivel weight, but with the 4 m leaders there was either virtually no difference (100 g swivels) or the difference was evident only in the last few seconds of the profiles (60 g and 160 g swivels). On average, 18 s after water entry all but two of the nine combinations for live fish bait had not reached 4 m depth. Dead baits were 5–10 m deep after this time. The difference between dead and live bait was greatest for the 2 m leaders and least for the 4 m leaders, with the contrast being most evident in the 160 g × 2 m combination.

Table 1. Results of the LMM for live and dead fish (yellow-tail mackerel and blue mackerel) testing for the effects of swivel weight, leader length, and bait life status on the sink rates of baited hooks in the 0–6 m depth of the water column (corresponds to ≤18 s elapsed time)

Source of Variation	Df	Wald statistic*	Pr (>F)
Time	17	4986.4	**<0.001**
Time × swivel wgt	36	127.2	**<0.001**
Time × leader length	36	122.2	**<0.001**
Time × bait spp.	18	16.1	0.588
Time × bait life status	18	101.0	**<0.001**
Time × swivel wgt × leader length	72	81.7	0.203
Time × leader length × bait life status	36	75.7	**<0.001**
Time × swivel wgt × bait life status	36	43.6	0.211
Time × swivel wgt × bait spp.	36	27.3	0.851
Time × leader length × bait spp.	36	21.2	0.976
Time × bait spp. × bait life status	18	28.0	0.062

Data for squid bait was excluded because live squid is not used in the fishery. Squid bait is included in Table 2. Values that are statistically significant ($P < 0.001$) are emboldened.
*Sequential Wald Statistic approximated chi-squared distribution.

Table 2. Results of the LMM for the dead bait group (yellow-tail mackerel, blue mackerel and squid) examining the effects of swivel weight, leader length and bait species on the sink rates of baited hooks

Source of Variation	Df	Wald statistic*	Pr(>F)
Time	17	12350.9	**<0.001**
Time × swivel wt	36	141.7	**<0.001**
Time × leader length	36	328.0	**<0.001**
Time × bait spp.	36	47.1	0.102
Time × swivel wt × leader length	72	119.9	**<0.001**
Time × swivel wt × bait spp.	72	58.0	0.884
Time × leader length × bait spp.	72	56.8	0.905
Time × swivel wt × leader length × bait spp.	144	122.1	0.907

The analysis includes dead baits only (both species of fish and one species of squid). Values that are statistically significant ($P \leq 0.001$) are shown in emboldened type. *Sequential Wald Statistic approximated chi-squared distribution.

Individual sink profiles of live fish bait (Figure 4(a)) were much more variable than dead fish bait (Figure 4(b)). The profiles for live blue mackerel to 120 s after deployment revealed a persistent high degree of variability, indicating that baits were swimming around in the water column against the weight of the swivels (Appendix C). Some individual live baits were still <10 m beneath the surface after 120 s. Comparable data for individual dead baits are not presented because at the 18 s mark sink profiles were more-or-less linear, indicating that baits would have continued sinking at a constant rate until branch lines became taut on the mainline.

Dead baits: fish and squid

As with the fish baits alone, the inclusion of squid made no statistically detectible difference to the sink profiles (Table 2), so the data were averaged over the three species. There was a statistically significant interaction between swivel weight and leader length (Table 2). The source of the interaction is revealed in Figure 5, which presents the results in two forms – leader length as a function of swivel weight and swivel weight as a function of leader length.

Within the 60 g and 100 g swivels (Figure 5(a)), baited hooks on 2 m and 3 m leaders sank at identical rates and both

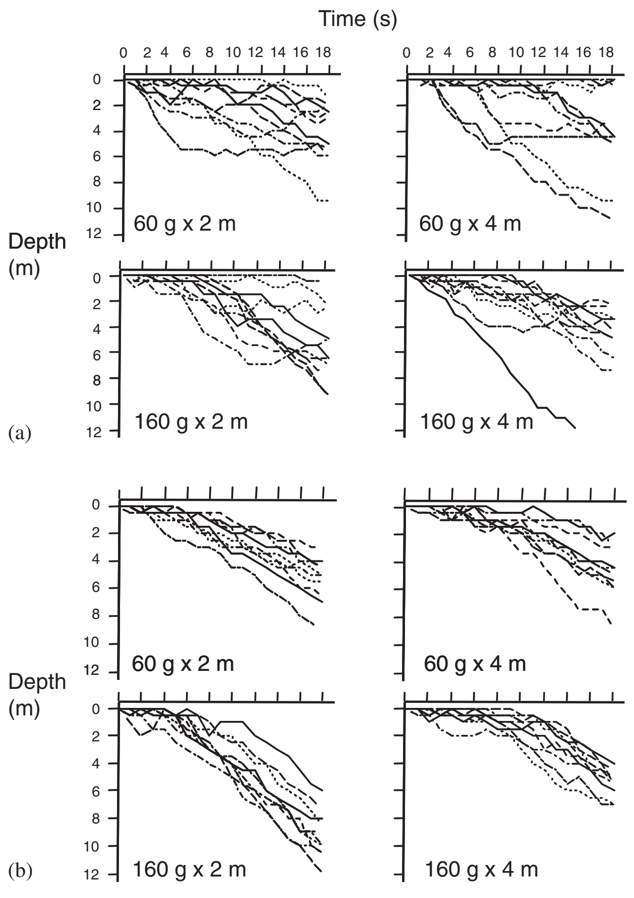

Figure 4. Examples of sink profiles of (a) individual live blue mackerel bait and (b) individual dead blue mackerel bait as a function of swivel weight and leader length in the first 18 s after deployment (corresponds to 0–6 m depth).

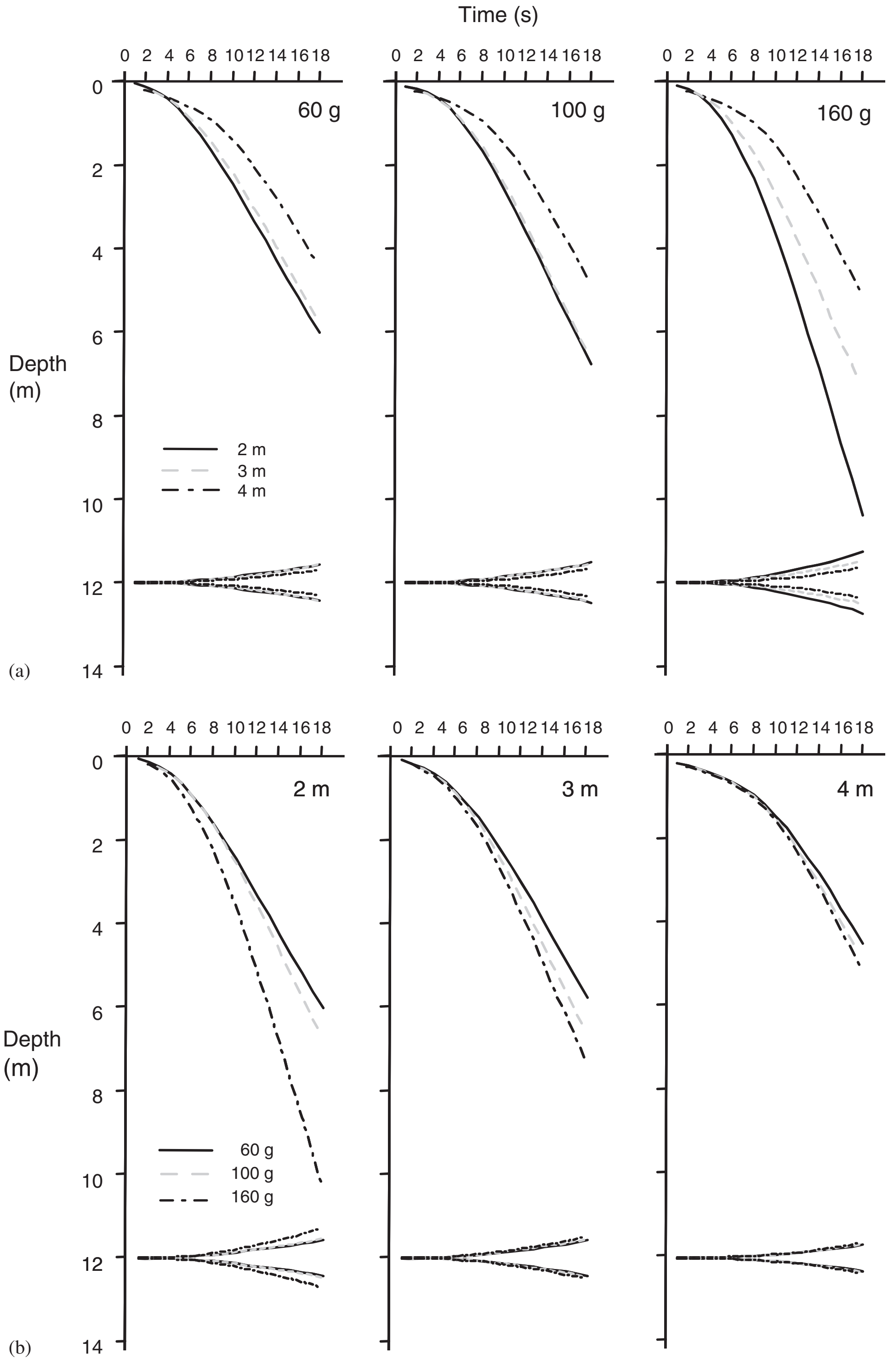

Figure 5. Mean sink profiles for the three species of dead baits (yellow-tail mackerel, blue mackerel and squid) in the first 18 s after deployment. The data are presented as (a) leader length as a function of swivel weight and (b) swivel weight as a function of leader length. Data for the three bait species have been averaged ($n = 33$ for each combination). See Methods for interpretation of confidence bounds.

sank significantly faster than gear with 4 m leaders. In contrast the sink profiles for all three leaders with 160 g swivels were significantly different. Within leader length (Figure 5(b)), the sink profiles of all three swivel weights with 4 m leaders were statistically inseparable. Within 3 m leaders, only the profiles for 60 g and 160 g swivels were statistically different and within the 2 m leaders the 160 g swivels sank significantly faster than the two lighter swivels, which were statistically inseparable.

Sink rates: live bait

The mean sink times and rates for all combinations of swivel weight and leader length are shown in Table 3.

Table 3. Comparison of mean sink times and mean sink rates among dead and live blue mackerel and yellow-tail mackerel for different swivel weights and leader lengths in the 0–6 m depth range (≤20 s elapsed time)

Life status	Swivel wt. (g)	Leader length (m)	Mean sink time (s)			Mean sink rate (m s^{-1})		
			0–6 m	0–2 m	4–6 m	0–6 m	0–2 m	4–6 m
Dead	60	2	17.0	8.6	3.9	0.35 (0.02)	0.23	0.48
Live	60	2	*	13.4	*	*	0.15	*
Dead	60	3	19.1	9.5	4.2	0.31 (0.02)	0.21	0.48
Live	60	3	*	11.9	*	*	0.16	*
Dead	60	4	*20	12.5	*	*	0.16	*
Live	60	4	*	13.1	*	*	0.15	*
Dead	100	2	16.7	8.6	4.2	0.36 (0.02)	0.23	0.50
Live	100	2	*	12.2	*	*	0.16	*
Dead	100	3	17.6	9.2	4.2	0.34 (0.02)	0.22	0.49
Live	100	3	*	10.4	*	*	0.19	*
Dead	100	4	19.1	11.0	4.3	0.31 (0.03)	0.18	0.46**
Live	100	4	*	11.0	*	*	0.18	*
Dead	160	2	13.4	7.4	2.7	0.45 (0.02)	0.27	0.74
Live	160	2	19.7	8.9	4.2	0.30 (0.02)	0.22	0.48
Dead	160	3	15.8	8.3	3.6	0.38 (0.02)	0.24	0.59**
Live	160	3	18.2	8.6	4.8	0.33 (0.02)	0.23	0.42
Dead	160	4	19.7	11.0	3.6	0.30 (0.02)	0.18	0.54**
Live	160	4	20.0	9.8	4.2	0.30 (0.02)	0.19	0.47

Within life status data for both species of fish are combined (see text; $n = 22$ for each row). Times and rates are presented as (a) cumulative values for entire profiles (for 0–6 m), (b) times/rates for the initial stage of sink profiles (0–2 m) and (c) times/rates for the final stage of profiles (4–6 m). Estimates in parentheses beside mean sink rates for the 0–6 m range are 1 s.e. *After 20 s had not reached maximum depth in range. **Probably still accelerating (see text).

The time axis in the table has been extended from 18 s to 20 s to increase the number of combinations that reached 6 m depth. Only live bait attached to gear with 160 g swivels reached this depth after 20 s. Mean initial rates ranged between 0.15 m s^{-1} (60 g × 2 m) and 0.23 m s^{-1} (160 g × 3 m). Mean final sink rates for 160 g swivels ranged from 0.42–0.47 m s^{-1}.

Sink rates: dead bait

All swivel weights and leader length combinations for dead baits reached 6 m after 18 s except the 60 g × 4 m combination (Table 3). Mean initial sink rates ranged from 0.18–0.27 m s^{-1} and mean final rates ranged from 0.48 (60 g × 2 m)–0.74 (160 g × 2 m) m s^{-1}, 2–3 times faster than initial rates. The estimates for the final rates in Table 3 for 4 m leaders are not indicative of actual rates because at this depth gear on 4 m leaders should still be accelerating. Final rates for gear with 4 m leaders should be similar to those for 2 m leaders (i.e. 0.74 m s^{-1} for the 160 g × 4 m combination). Within each swivel weight, mean initial sink rates were inversely proportional to leader length (the shorter the leaders the faster the sink rate). In general, mean final sink rates increased as swivel weight increased. For example, the 160 g × 2 m combination sank, on average, 1.5 times faster then the 60 g × 2 m combination.

DISCUSSION

Bait species

There were no detectible differences in sink profiles/rates between the two species of live bait and between the three species of dead bait. This is hardly surprising with live bait because the individual profiles were highly variable, but differences might have been expected with the dead forms due to differences in length and mass of the baits. In a static water trial in the same tank described in Appendix A, the final sink rate of the same three bait species used on the *Assassin* differed significantly ($P < 0.001$ for all comparisons) with the smallest bait (yellow-tail mackerel) sinking fastest and the largest (squid) sinking slowest (Robertson and van den Hoff, 2010). However, these results, while indicative of what might be expected at sea if a very large number of replicates had been completed, are not representative of results obtained in fishing operations subjected to variation in gear deployment technique, variation in amount of slack in leaders, orientation of baits when they land in the water, propeller turbulence and sea state. That differences were not detected with the 11 replicates in the experiment indicates that the effect of bait species was minor and overridden in importance by the other effects examined.

Live bait

The most important findings for live bait were (a) the interaction between life status and leader length, and (b) the high degree of variation in individual sink profiles and slow sink rates for both the 18 s and 120 s time periods.

The statistical interaction between bait life status and leader length means the latter cannot be considered in isolation of the former. Mean live versus dead bait sink profiles of the 2 m and 3 m leaders (all swivel weights) differed markedly, but profiles for the 4 m leaders were either virtually the same (100 g swivels) or the differences were relatively small (60 g and 160 g swivels). This suggests that longer leaders tend to be associated with smaller sink rate differences between live and dead bait. There could be two reasons for this – live bait sinks faster, on average, on long leaders and/or dead bait sinks slower on long leaders (as shown in Figure 5). Underwater observations off a stationary fishing vessel suggest the natural tendency of live yellow-tail mackerel is to dive away from the surface. When leaders become taut the swivel drags on the fish and causes it to struggle, which impedes sinking. 4 m leaders take longer than 2 m leaders to become taut, providing more time for fish to swim away from the surface before being pulled by the swivel.

Nonetheless, there is little evidence in Figure 3 that longer leaders change the shape of the profiles. In fact, with the exception of 160 g swivels on 2 m and 3 m leaders, the sink profiles of live bait are much the same and not greatly affected by changes to swivel weights or leader lengths. Presumably this is because the branch lines observed underwater were thrown with slack in the leaders, whereas branch lines on the *Assassin* were deployed with the leaders almost taut. The live bait profiles in Figure 3 probably indicate a high incidence of struggling by the majority of baits against the drag of the swivels.

While the mean sink profiles aid in understanding the relationships between the various effects, the sink rates of individual live baits are probably more relevant to seabird conservation because the slowest sinking baits are likely to present the greatest risks to seabirds. Before the experiment there was speculation in the ETBF that live bait sinks faster than dead bait because live fish swim away from the surface as a defence mechanism. The results to 18 s and 120 s after deployment show that live baits behaved erratically, making generalizations impossible. A small number of individuals did, indeed, sink quickly, exceeding 10 m depth in only 16 s ($>0.6\,\mathrm{m\ s^{-1}}$). However, by the 18 s mark the majority had reached less than half that depth and some were still swimming within 2 m of the surface. There was no consistent pattern in this – individual baits on the $60\,\mathrm{g} \times 4\,\mathrm{m}$ combination were just as likely to be near the surface as those on the $160\,\mathrm{g} \times 2\,\mathrm{m}$ combination. This erratic swimming behaviour persisted until at least the 120 s mark, when some baits were <10 m deep and one bait ($60\,\mathrm{g} \times 3\,\mathrm{m}$ group) was within 2 m of the surface.

Dead bait: sink profiles

The most important findings for the dead bait species were (a) the statistical interaction between swivel weight and leader length in Figure 5, and (b) the influence of these effects on the initial sink rates.

The source of the interaction between swivel weight and leader length is the almost identical profiles for 2 m and 3 m leaders with 60 g and 100 g swivels compared with profiles for all three leader lengths with 160 g swivels, which differed markedly. Shortening leaders with the two lighter swivels was only partially effective compared with shortening gear with 160 g swivels, where each 1 m reduction in leader length significantly increased the sink rate. Thus, if priority is given to swivel weight, to significantly improve the sink profiles of all three leader lengths required the use of the heaviest swivels. Expressed the other way (swivel weight as a function of leader length) within 3 m and 4 m leaders, simply increasing the weight of the swivels made little or no difference to the profiles, nor did adding 40 g to the weight of a 60 g swivel (to make 100 g) on 2 m leaders. Thus, if priority is given to leader lengths, 160 g swivels on 2 m leaders is required to significantly improve the sink profiles.

Dead bait: initial sink rates

As with live bait, the LMM analysis for the dead bait group in Table 2 and the presentation in Figure 5 treat all the data in the profiles as a continuum. This masks differences that may exist in the critical shallow depths, which are where baits are most accessible, and visible, to seabirds. Shortening leaders from 3 m to 2 m increases the average initial sink rates. The improvement for 60 g swivels was $0.02\,\mathrm{m\ s^{-1}}$ compared with $0.05\,\mathrm{m\ s^{-1}}$ from 4 m to 3 m (the results for 100 g swivels were similar to those for 60 g). This results in a $\sim$10% reduction in time baits are in the shallow depths, which might be important to seabirds. The comparable results for 160 g swivels are $0.03\,\mathrm{m\ s^{-1}}$ and $0.06\,\mathrm{m\ s^{-1}}$ for leaders reduced from 3 m to 2 m and from 4 m to 3 m, respectively. The former equates to $\sim$25% less time taken for baits to clear surface waters. The most striking comparison was the $160\,\mathrm{g} \times 2\,\mathrm{m}$ and $60\,\mathrm{g} \times 4\,\mathrm{m}$ combinations, the former taking 40% less time to reach 2 m depth than the latter.

Combining the assessments above for the entire profiles and initial sink rates, the results are what would be expected intuitively: most benefit is derived by placing heavy swivels close to hooks. Short leaders are associated with fast initial sink rates and heavy swivels are associated with fast final sink rates. The results also show that small changes to swivel weights and leader lengths are unlikely to be detectable at sea and unlikely to yield an appreciable reduction in seabird mortality. Therefore, if 60 g is the basis for comparison a doubling of this weight would be a useful starting point to improve sink rates to deter seabirds. With regard to the leaders, the proportional improvement in initial sink rate decreases as leader length decreases (in the 2–4 m range) unless very heavy weights are used. For swivels of conventional size (60–75 g) 1 m leaders may confer little additional advantage over 2 m leaders. The latter would be a practical compromise. This does not, of course, refute the potential benefit of placing weight at the hook itself, which would eliminate the lag at the surface associated with long leaders.

Implications for seabird conservation

At the time of the experiment weighted branch lines were not used in the ETBF. In an effort to reduce seabird mortality below the regulated threshold (<0.05 birds per 1000 hooks) the Australian Fisheries Management Authority (AFMA) and industry completed trials involving 38 g, 60 g and 100 g swivels in combination with bird scaring streamer lines. The results of these trials were inconclusive, partly because of poor compliance levels to the required line weighting regimes (leaders ranged to 6 m; G. Robertson, personal observations). Insights from the *Assassin* experiment enables speculation on the likelihood that these three weighting regimes improved the sink rates. The 40 g difference between 60 g and 100 g swivels used on the *Assassin* made no discernible difference with dead bait, either at the surface or deeper down; this would also be expected with the seabird trial. Similarly, the transition from 38 g to 60 g is unlikely to have made a discernible increase in the sink rates. An improvement should have been detectable with the addition of 38 g swivels to unweighted gear if the weight was placed close to the hook, but not 6 m away. As revealed in Figure 5(b) long leaders greatly accentuate the time lag at the surface and virtually negate the benefit of line weighting.

The implications for seabird conservation regarding live bait are more clear-cut. The use of live bait in the ETBF is associated with higher seabird by-catch rates (Trebilco *et al.*, 2010). 18 s after deployment the majority of live baits set from the *Assassin* were swimming within a few metres of the surface and some were still at relatively shallow depths after 120 s.

After these two time periods baits would be $\sim$74 m and $>$490 m astern (at 8 knots setting speed), respectively, greatly reducing the effectiveness of the bird scaring streamer lines (prescribed minimum aerial extent: 90 m). These results explain why the use of live bait in the ETBF greatly increases the exposure of baited hooks to seabirds and is one of the reasons why vessels using live bait experience higher seabird by-catch rates than vessels using dead bait.

Implementation in the ETBF

Line weighting requirements became a mandatory part of fishing permits under the Australian government's Fisheries Management Act 1992 in June 2007. Permit holders were required to equip branch lines with either 60 g swivels $\leq$3.5 m from hooks, or 100 g swivels $\leq$4 m from hooks. Baited hooks with these weighting regimes sink at similar rates, but both were permitted out of deference to proactive fishermen who had already purchased these swivels. In the winter (April–September) season of 2008 the seabird by-catch rate was breached by five vessels off south-eastern Australia, prompting a day setting prohibition in that sector of the fishery. Of the 12 seabird captures involved, evidence as to the adequacy of the mitigation was unambiguous for only two of the captures (G. Robertson, personal observations). These captures, both albatrosses (*Thalassarche* spp.), indicated that the mandated line weighting in combination with a single streamer line (with dead and live bait and day setting) could not prevent the seabird catch rate from being exceeded under all conditions and that other approaches were required.

FUTURE RESEARCH

It is usually the case that mitigation measures must fail to achieve conservation targets before stakeholders embrace alternatives more likely to be successful. This is understandable due to fiscal and operational issues regarding the alternatives and the absence of clear evidence about necessity. To produce discernible changes to sink rates compared with those attained by 60 g swivels on 3.5 m leaders may require gear to be configured with swivels $\geq$120 g, $\leq$2 m from hooks. The evidence in support of $\leq$2 m leaders is clear, that for 120 g swivels less so. However, it is neither practical nor economically viable to consider swivels as heavy as 160 g. Swivels of 120 g should sink distinctly faster than 60 g swivels and would be a useful compromise in further experiments to expedite sink rates to deter seabirds. An alternative to this regime would be a smaller amount of weight at the hook. The exact amount of weight would have to be determined experimentally.

ADVICE TO MANAGEMENT

The evidence suggests that the use of live bait in pelagic longline fisheries will increase seabird mortality above that associated with the use of dead bait. In fisheries that do not currently use live bait management agencies should consider prohibiting the use of live bait to limit potential impacts on seabirds. With dead bait, the small changes to swivel weights and leader lengths typically preferred by industry are unlikely to be detectible at sea and unlikely to substantially reduce the incidental take of seabirds. We suggest that future research to reduce seabird mortality from that associated with 60 g swivels 3–4 m from hooks include in assessments gear configured with 120 g swivels $\leq$2 m from hooks and gear with a smaller amount of weight placed at the hook.

ACKNOWLEDGEMENTS

We are grateful to Pavo Walker, owner/operator of the *Assassin*, and the crew of the *Assassin* for their support for this study. We thank Martin Scott of the Australian Fisheries Management Authority for his assistance with the work at sea. We are grateful to Mary-Anne Lea and Tammy McGowan for undertaking the onerous task of summarizing the TDR data into spreadsheets and checking the data quality before analysis. We appreciate the assistance of John Van Den Hoff with the static water trial of TDR effects and Erik Poole of the Sydney Fish Markets for providing the fish for that trial. Comments by Ian Hay, Barry Baker and three anonymous referees improved a draft.

REFERENCES

AAD. 2006. *Threat Abatement Plan for the Incidental Catch* (*or Bycatch*) *of Seabirds During Oceanic Fishing Operations*, *2006*. Australian Antarctic Division, Department of the Environment, Water, Heritage and the Arts.

ACAP. 2007. Report of the first meeting of the Seabird Bycatch Working Group of the Agreement on the Conservation of Albatrosses and Petrels. Third Meeting of Advisory Committee, Valdivia, Chile, 19–22 June 2007.

Agnew DJ, Black AD, Croxall JP, Parkes GB. 2000. Experimental evaluation of the effectiveness of weighting regimes in reducing seabird by-catch in the longline toothfish fishery around South Georgia. *CCAMLR Science* **7**: 119–131.

Baker GB, Wise BS. 2005. The impact of pelagic longline fishing on the flesh-footed shearwater *Puffinus carneipes* in Eastern Australia. *Biological Conservation* **126**: 306–316.

Bugoni L, Neves TS, LeiteJr. NO, Carvalho D, Sales G, Furness RW, Stein CE, Peppes FV, Giffoni BB, Monteiro DS. 2008. Potential bycatch of seabirds and turtles in hook-and-line fisheries of the Itaipava Fleet, Brazil. *Fisheries Research* **90**: 217–224.

Dietrich KS, Melvin EF, Loveday C. 2008. Integrated weight longlines with paired streamer lines — best practice to prevent seabird bycatch in demersal longline fisheries. *Biological Conservation* **141**: 1793–1805.

Diggle PJ, Heagerty P, Liang K, Zeger SL. 2001. *Analysis of Longitudinal Data*, 2nd edn. Oxford University Press: Oxford.

Fishing News International. 2009. Big changes in pacific tuna fishing **48**: 24–25.

Gilmour RA, Thompson R, Cullis BR. 1995. Average information REML: An efficient algorithm for variance parameter estimation in linear mixed models. *Biometrics* **51**: 1440–1450.

Gilmour RA, Cullis BR, Welham SJ, Thompson R. 1999. *Asreml Reference Manual*. *Biometric Bulletin No. 3*. Orange Agricultural Institute: Orange, NSW, Australia.

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

Melvin EF, Walker N. 2008. Optimizing tori line designs for pelagic tuna longline fisheries. Report of work under New Zealand Ministry of Fisheries Special Permit 355. CCSBT-ERS/0909/17.

Melvin EF, Heinecken C, Guy T. 2009. Optimizing tori line designs for pelagic tuna longline fisheries: South Africa.

Report of work under special permit from the Republic of South Africa Department of Environmental Affairs and Tourism, Marine and Coastal Management, Pelagic and High Seas Fishery Management Division. 29 September 2008.

Moreno CA, Castro R, Mújica LJ, Reyes P. 2008. Significant conservation benefits obtained from the use of a new fishing gear in the Chilean Patagonian toothfish fishery. *CCAMLR Science* **15**: 79–91.

Petersen SL, Nel DC, Ryan PG, Underhill LG. 2008. Understanding and mitigating vulnerable bycatch in southern African trawl and longline fisheries. WWF South Africa Report Series – 2008/Marine/002.

R Development Core Team. 2006. *R*: *A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Robertson G, van den Hoff J. 2010. Static water sink rate trials to improve understanding of sink rates estimated at sea. Third Meeting of the Seabird Bycatch Working Group of the Agreement on the Conservation of Albatrosses and Petrels. Mar del Plata, Argentina, 8–10 April 2010.

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

Robertson G, Moreno CA, Crujeiras J, Wienecke B, Gandini P, McPherson G, Seco Pon JP. 2008a. An experimental assessment of factors affecting the sink rates of Spanish-rig longlines to minimise impacts on seabirds. *Aquatic Conservation*: *Marine and Freshwater Ecosystems* **17**: S102–S121.

Robertson G, Moreno CA, Gutiérrez E, Candy SG, Melvin EF, Seco Pon JP. 2008b. Line weights of constant mass (and sink rates) for Spanish system Patagonian toothfish longline vessels. *CCAMLR Science* **15**: 93–106.

Robertson G, Candy SG, Wienecke B. 2010. Effect of line shooter and mainline tension on the sink rates of pelagic longlines and implications for seabird interactions. *Aquatic Conservation*: *Marine and Freshwater Ecosystems* **20**: 419–427.

Rodriguez-Marin E, Arrizabalaga H, Ortiz M, Rodriguez-Cabello C, Moreno G, Kell LT. 2003. Standardization of blue fin tuna, *Thunnus thynnus*, catch per unit effort in the baitboat fishery of the Bay of Biscay (Eastern Atlantic). *ICES Journal of Marine Sciences* **60**: 1216–1231.

Trebilco R, Gales R, Lawrence E, Alderman R, Robertson G, Baker GB. 2010. Seabird bycatch in the Eastern Australian Tuna and Billfish pelagic longline fishery: temporal, spatial and biological influences. *Aquatic Conservation*: *Marine and Freshwater Ecosystems* **20**: 531–542.

Waugh SM, MacKenzie DI, Fletcher D. 2008. Seabird bycatch in New Zealand trawl and longline fisheries, 1998–2004. *Papers and Proceedings of the Royal Society of Tasmania* **14**: 45–66.

APPENDIX A

The following trials were conducted in a 3.0 m high, 2.0 m diameter tank of seawater at the Australian Antarctic Division to gain a measure of the effects on sink rates of the TDRs and light sticks used in the experiment at sea.

Effect of TDRs on sink rates

In this trial the diameter of monofilament branch line, bait species, hook type and hooking position in bait were the same as used in the experiment at sea (see Methods). Bait species used in the tank were dead yellow-tail mackerel and dead blue mackerel. These two species contrasted in size and were considered adequate to determine TDR effects. The yellow-tail mackerel (20.0 cm; 113.2 g) and blue mackerel (28.4 cm; 269.7 g) were similar to the average sizes of these species used at sea. For each bait species the same individual bait was used. Leaded swivel weights were 60 g, 100 g and 150 g, the latter being 10 g less than the heaviest swivel used at sea. The TDR was attached with miniature cable ties 0.20 m from the eye of the hook. For each bait species and swivel weight, 15 drops were performed with an Mk9 TDR attached and 15 without a Mk9 TDR attached. Sink rates were recorded to the nearest 0.01 s with a digital stop watch. Because the drop depths varied with initial and final sink rates (see text), data were analysed as sink rates to known depths by one-factor analyses of variance.

Initial sink rate varies as a function of the distance between swivel and hook when gear lands in the water. Since in the experiment at sea the swivels and bait hooks were thrown such that the joining line was almost taut, this configuration was replicated in the tank. The swivel and baited hook were joined by a 1.5 m section of monofilament with a further 1.5 m of line lying loosely in the water (simulating a 3.0 m leader length). The swivel and baited hook were held 1.5 m apart horizontal to the water surface, released simultaneously and the swivel timed to the tank floor. At that point the baited hook had reached 1.5 m depth (e.g. the 3.0 m depth of the tank minus the 1.5 m distance between hook and swivel). Final sink rate was simulated by attaching the swivel 0.40 m from the baited hook and holding the bait horizontal to the water surface, which allowed the swivel and TDR to hang beneath it. The baited hook was released and timed to the tank bottom. The results are shown in Table A1.

The addition of a TDR to yellow-tail mackerel with a 60 g swivel slowed the initial sink rate by, on average, 0.01 m s^{-1}. No TDR effect was detected on the final sink rate. Similarly, the TDR slowed the initial sink rate of blue mackerel bait by, on average, 0.02 m s^{-1} and made no difference to the final sink rate. Based on these findings for the lightest of the three swivels (where a TDR effect should be most detectable), we conclude that the TDRs deployed from the *Assassin* had no effect on final sink rates and only a very minor effect on the initial sink rates.

Effect of light sticks on sink rates

To determine if plastic light sticks (8.7 × 1.0 cm, 7 g, neutrally buoyant) affected the sink rates of hooks baited with squid, a

Table A1. Mean (±s.d.) sink rates (initial and final) for yellow-tail mackerel (YTM) and blue mackerel (BM) for the lightest (60 g) of the three swivel weights associated with the presence and absence of a TDR. Each estimate is the result of 15 replicates

Bait species	Swivel (g)	Initial sink rate (m s^{-1})			Final sink rate (m s^{-1})		
		With TDR	Without TDR	P	With TDR	Without TDR	P
YTM	60	0.42 (0.01)	0.43 (0.01)	0.01	0.84 (0.02)	0.84 (0.01)	0.45
BM	60	0.39 (0.01)	0.41 (0.01)	0.006	0.77 (0.04)	0.77 (0.03)	0.97

squid (315 g; 19.8 cm mantle length) was attached to the same 60 g branch line used in the TDR trial. The 60 g swivel was the lightest of the three used at sea and considered the most likely to demonstrate a light stick effect if one existed. The distance between hook and swivel was the same as in the TDR trial. The squid bait was hooked in the same position as used at sea. A light stick was attached mid-way between hook and swivel (i.e. 0.20 m from the hook) on the branch line and the branch line dropped 15 times in the tank following the procedure described above for the TDRs. The light stick was then removed and the gear dropped a further 15 times. The results are shown in Table A2. Since there was no discernible difference in sink rates associated with presence or absence of a light stick for both initial and final sink rates it was assumed the use of light sticks with squid bait did not influence hook sink rates in the research at sea.

Table A2. Mean (± s.d.) sink rates (initial and final) of baited hooks with and without light sticks

Initial sink rate (m s^{-1})		Final sink rate (m s^{-1})	
With light stick	Without light stick	With light stick	Without light stick
0.302 (0.01)	0.294 (0.01)	0.443 (0.01)	0.438 (0.01)

APPENDIX B

Models of error structure

As in Robertson *et al.* (2008b), for both parametric and non-parametric LMMs the extra residual variance, in addition to the experimental unit (EU) variance, associated with each time for the response variable log(Depth+1) was estimated using the heterogeneous variance form of these LMMs. This involved an extra variance parameter to account for the greater variability of sink profiles for live baits about their mean profiles for given fixed factor combinations. Table B1 shows that the variance for the live bait profiles represented an increase of slightly more than 50% relative to profiles for dead baits. The estimated autocorrelation parameter was extremely high indicating the importance of including the correlation between depths within single profiles in the analysis. The variability between sets was relatively small and estimated with poor precision since there were only 11 sets. The corresponding estimates for the non-parametric LMMs fitted are not given since they were very similar to the estimates given in Table B1.

Table B1. Variance estimates and autocorrelation estimate for the non-parametric LLM used in the analysis presented in Table 2 shown earlier in the text

	Variance	s.e.	Z-ratio
Set	4.895×10^{-4}	9.933×10^{-4}	0.493
P-unit.BLS[dead]	0.0	—	—
P-unit.BLS[live]	6.389×10^{-2}	1.379×10^{-2}	4.633
EU residual variance	1.263×10^{-1}	5.155×10^{-3}	24.502
Autocorrelation	0.867	0.005	157.869

APPENDIX C

Sink profiles of individual live blue mackerel bait as a function of swivel weight and leader length in the first 120 s after deployment.