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

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ABSTRACT

1. While line weighting and other mitigation measures are mandatory in the pelagic longline fishery for tuna off Australia's east coast, some seabirds are still caught, suggesting that mitigation measures are not fully effective in all conditions. An experiment was conducted in that fishery to establish a scientific basis for potential changes to reduce seabird mortality; in particular, by evaluating different combinations of line weighting and other variables affecting line sink rates. The results of this experiment are directly relevant to pelagic longline tuna fisheries in the Indian Ocean.
2. 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.
3. On average, live bait sank much slower than dead bait, greatly increasing the exposure of baited hooks to seabirds and hence the risk of bycatch. Sink rates of individual live bait were highly variable. Many were < 2 m underwater 18 seconds after deployment, including some on the heaviest swivels, and some were < 10 m deep after 120 seconds.
4. Within the dead bait group, gear with 60 g and 100 g swivels on the same leader length sank at similar rates, as did all three swivel weights on 4 m leaders. The 160 g x 2 m combination sank the fastest, averaging 0.27 m/s and 0.74 m/s from 0-2 m and 4-6 m, respectively. The 60 g x 4 m combination sank the slowest, averaging 0.16 m/s to 2 m depth and failing to attain 6 m depth after 18 seconds. Initial sink rates (0-2 m) were increased by placing leaded swivels close to hooks and final sink rates (> 4 m) by increasing the weight of the swivels.
5. The results indicate that the small (incremental) changes to the weight of leaded swivels and the length of leaders typically preferred by the fishing industry are unlikely to make an appreciable reduction in seabird mortality because resultant increases in sink rates will be insubstantial.
6. Changing line weighting regimes to reduce seabird mortality requires consideration of sink rates close to the surface (i.e. 0-2 m) in addition to cumulative rates to the deeper depths. To substantially reduce seabird mortality compared to that associated with 60 g swivels and ~3.5 m leaders (the preferred option by industry) may require branch lines be configured with swivels ≥ 120 g placed ≤ 2 m from hooks. An alternative to the latter regime would be to place a smaller amount of weight at or very close to the hook. The exact amount of weight would have to be determined experimentally.

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 requirement (e.g. if seabirds are of uncertain conservation status) or ethical considerations of the researchers and/or authorities granting permits (e.g. 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 (e.g. 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 sample sizes will be required, potentially resulting in an unacceptably 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. Line weighting has since become mandatory in the ETBF, with a consequent significant decrease in seabird bycatch.

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, 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 minimise 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 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 characterised by relatively slow sink rates. The second stage occurs shortly after deployment and is characterised by a linear (i.e. constant) sink

profile, and much faster sink rate, to target depths. The duration of these two stages is influenced 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 (Figure 1). 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 (e.g. 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 we refer to the first stage as the “initial” sink rate and the second as 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.

Figure 1

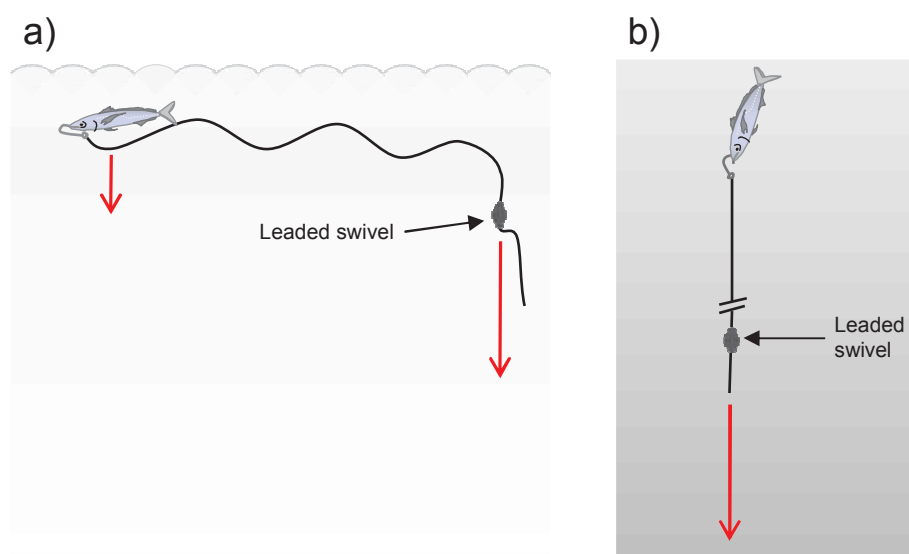


Figure 1. The source of the difference between the initial (part ‘a’) and final (part ‘b’) stages of line sinking. Landed baits sink slower than the leaded swivel until the length of line connecting them becomes taut. The initial sink rate is influenced primarily by leader length (swivel weight has a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

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.

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) 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, identical to the vessel setting speed. By 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 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 seconds), 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 x 3 x 3 design yielded 45 combinations of factors and levels within factors (Figure 3).

A total of 45 branch lines was 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.

Figure 2

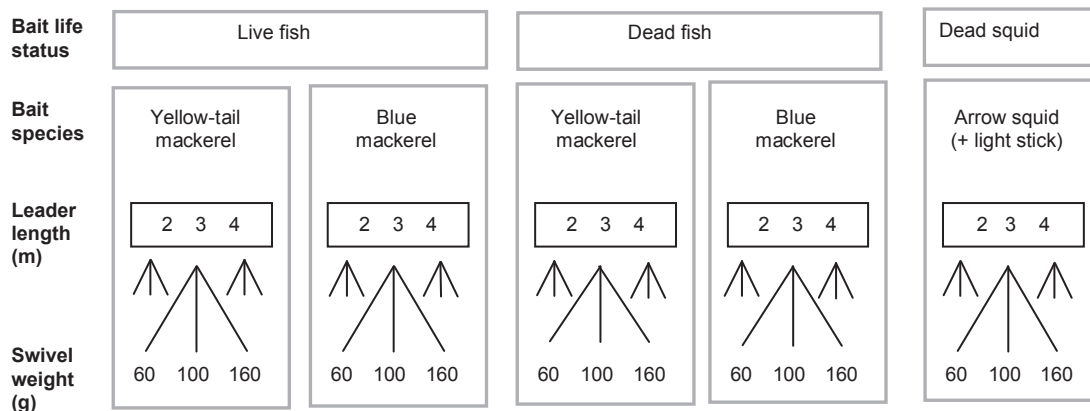


Figure 2. Experimental design showing the hierarchical order of factors testing for the effects of bait life status, bait species, leader lengths and swivel weights on the sink rates of baited hooks. The figure has been simplified for clarity. The boxes around bait species highlight the absence of live 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.

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 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 x 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 metres of mainline and buoys (but not branch lines) were deployed prior to the first hook being set. Similarly, so 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 second 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 the 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). 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. By 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.* 1994) 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 9 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 in the Results 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 5a, 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/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 m) and final (4-6 m) stages of the sink profiles mentioned earlier.

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 detectable 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). Eighteen seconds 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 x 2 m combination.

Table 1

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

*sequential Wald Statistic approximated Chi-squared distribution

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 seconds elapsed time). 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.

Figure 3

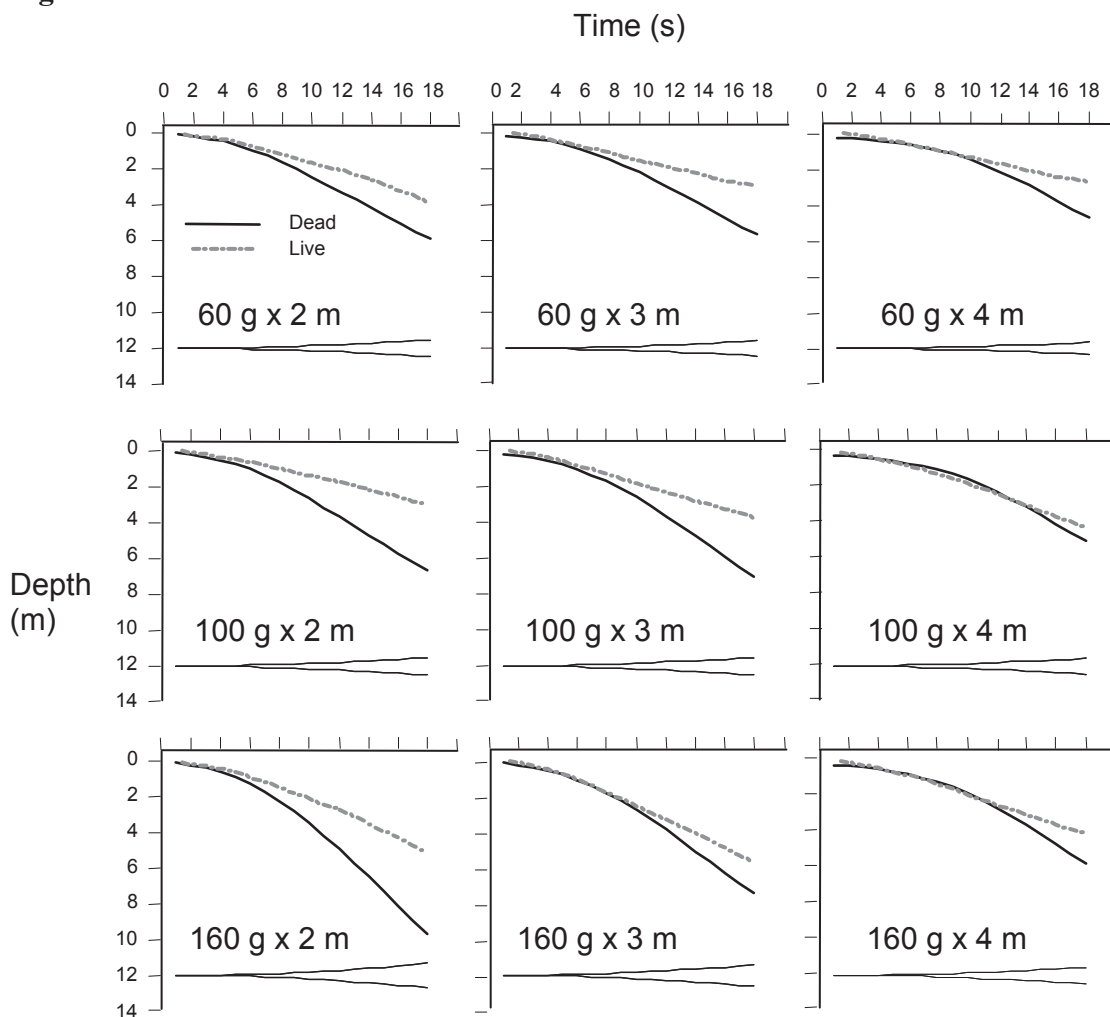


Figure 3. Mean sink profiles of dead and live yellow-tail mackerel and blue mackerel bait in relation to swivel weight and leader lengths in the first 18 s after deployment. Data for both fish species have been averaged (see text and Table 1). See Methods for interpretation of confidence bounds. $n =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

Individual sink profiles of live fish bait (Figure 4a) were much more variable than dead fish bait (Figure 4b). 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.

Figure 4

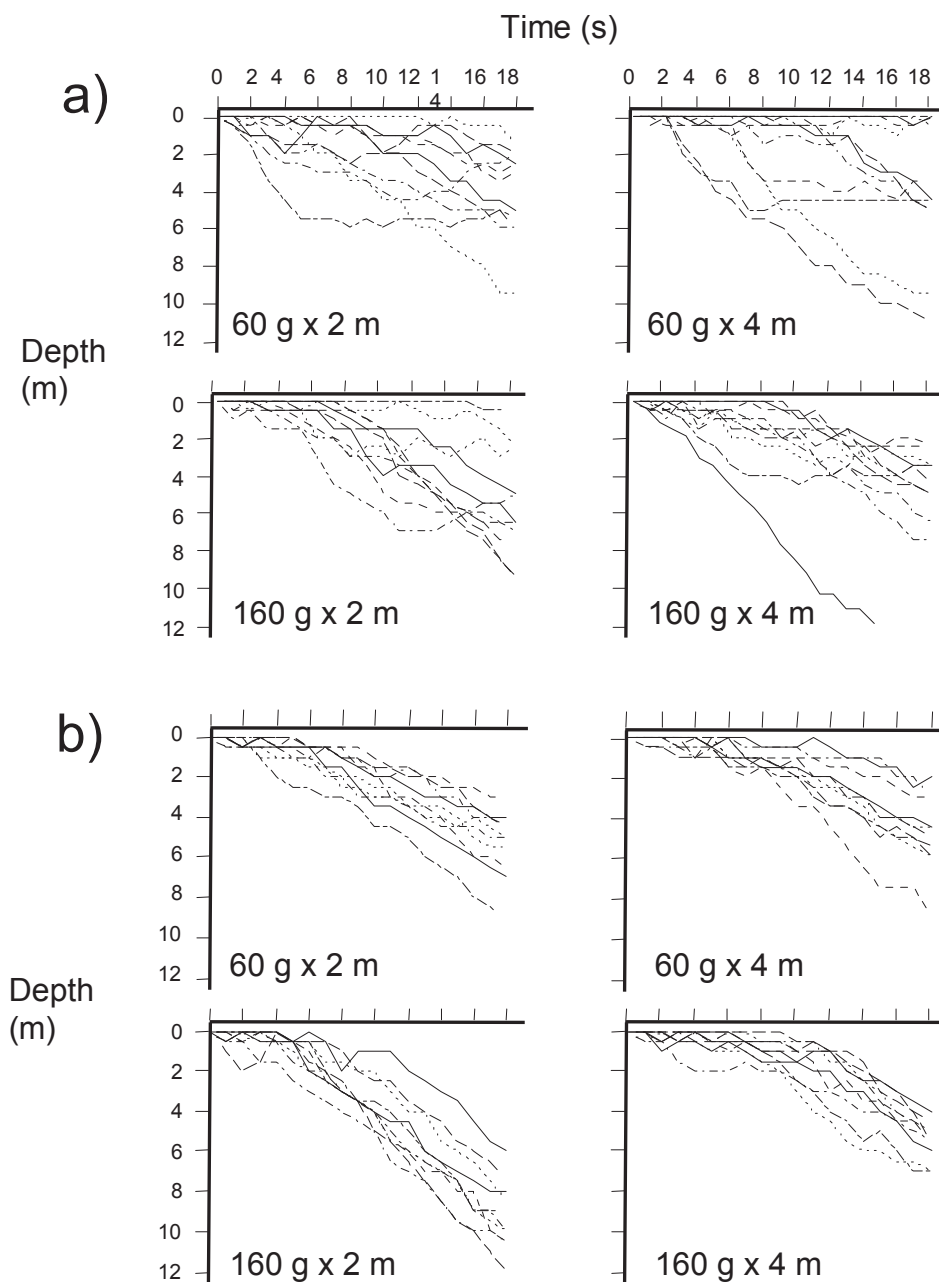


Figure 4. Examples of sink profiles of a) individual live blue mackerel bait and b) individual dead blue mackerel bait as a function of swivel weight and leader length in the first 18 s after deployment (corresponds to 0-6 m depth).

Dead baits: fish and squid

As with the fish baits alone, the inclusion of squid made no statistically detectable 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 6, 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 5a), baited hooks on 2 m and 3 m leaders sank at identical rates and both 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 5b), 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.

Table 2

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

*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. 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.

Figure 5

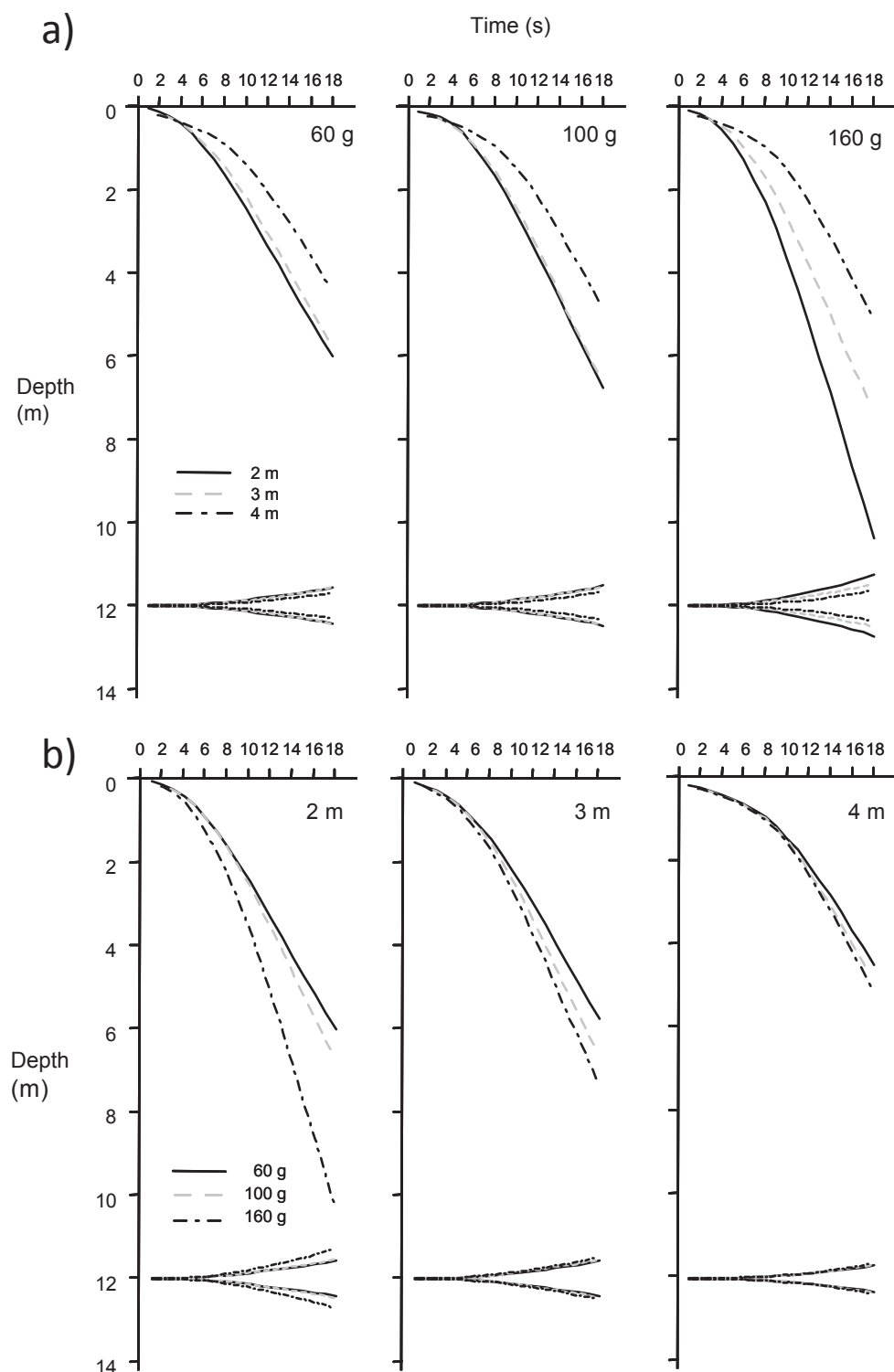


Figure 5. Mean sink profiles for the three species of dead baits (yellow-tail mackerel, blue mackerel and squid) in the first 18 s after deployment. The data are presented as: a) leader length as a function of swivel weight and b) swivel weight as a function of leader length. Data for the three bait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

Sink rates: live bait

The mean sink times and rates for all combinations of swivel weight and leader length are shown in Table 3. 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 (60 g x 2 m) and 0.23 m/s (160 g x 3 m). Mean final sink rates for 160 g swivels ranged from 0.42-0.47 m/s.

Sink rates: dead bait

All swivel weights and leader length combinations for dead baits reached 6 m after 18 seconds except the 60 g x 4 m combination (Table 3). Mean initial sink rates ranged from 0.18 to 0.27 m/s and mean final rates ranged from 0.48 (60 g x 2 m) to 0.74 (160 g x 2 m) m/s, 2 to 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 for the 160 g x 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 x 2 m combination sank, on average, 1.5 times faster than the 60 g x 2 m combination.

Table 3

Life status	Swivel wgt. (g)	Leader length (m)	Mean sink time (s)			Mean sink rate (m/s)		
			0-6 m	0-2 m	4-6 m	0-6 m	0-2 m	4-6 m
Live	60	2	*	13.4	*	*	0.15	*
Live	60	3	*	11.9	*	*	0.16	*
Live	60	4	*	13.1	*	*	0.15	*
Live	100	2	*	12.2	*	*	0.16	*
Live	100	3	*	10.4	*	*	0.19	*
Live	100	4	*	11.0	*	*	0.18	*
Live	160	2	19.7	8.9	4.2	0.30 (0.02)	0.22	0.48
Live	160	3	18.2	8.6	4.8	0.33 (0.02)	0.23	0.42
Live	160	4	20.0	9.8	4.2	0.30 (0.02)	0.19	0.47

Life status	Swivel wgt. (g)	Leader length (m)	Mean sink time (s)			Mean sink rate (m/s)		
			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
Dead	60	3	19.1	9.5	4.2	0.31 (0.02)	0.21	0.48
Dead	60	4	*20	12.5	*	*	0.16	*
Dead	100	2	16.7	8.6	4.2	0.36 (0.02)	0.23	0.50
Dead	100	3	17.6	9.2	4.2	0.34 (0.02)	0.22	0.49
Dead	100	4	19.1	11.0	4.3	0.31 (0.03)	0.18	0.46**
Dead	160	2	13.4	7.4	2.7	0.45 (0.02)	0.27	0.74
Dead	160	3	15.8	8.3	3.6	0.38 (0.02)	0.24	0.59**
Dead	160	4	19.7	11.0	3.6	0.30 (0.02)	0.18	0.54**

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 seconds elapsed time). 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. **likely still accelerating (see text).

DISCUSSION

Bait species

There were no detectable 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. Four metre 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 4 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. Prior to 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 generalisations impossible. A small number of individuals did, indeed, sink quickly, exceeding 10 m depth in only 16 s (> 0.6 m/s). 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 g x 4 m combination were just as likely to be near the surface as those on the 160 g x 2 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 g x 3 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 to profiles for all three leader lengths with 160 g weights, which differed markedly. Shortening leaders with the two lighter swivels was only partially effective compared to 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 m/s compared to 0.05 m/s from 4 m to 3 m (the results for 100 g swivels were similar to those for 60 g). This results in a ~ 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 m/s and 0.06 m/s for leaders reduced from 3 m to 2 m and from 4 m to 3 m, respectively. The former equates to ~ 25 % less time taken for baits to clear surface waters. The most striking comparison was the 160 g x 2 m and 60 g x 4 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 grams 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 (although they have since become mandatory and seabird bycatch has significantly reduced). In an effort to reduce seabird mortality below the regulated threshold (< 0.05 birds/1,000 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 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, 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 when placed 6 m away. As revealed in Figure 5b 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). Eighteen seconds 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 seconds. After these two time periods baits would be ~ 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 Fisheries Management Act 1991* in June 2007. Permit holders were required to equip branch lines with either 60 g swivels within 3.5 m from hooks, or 100 g swivels within 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 (May-September) season of 2008 the seabird by-catch rate was breached by five vessels off south-eastern Australia in the 30-35°S sector of the fishery, prompting a temporary prohibition on day setting in that sector until seabird abundance diminished. 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 are 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 to those attained by 60 g swivels on 3.5 m leaders may require gear to be configured with swivels $\geq \sim 120$ g at ≤ 2 m from hooks. The evidence in support of ≤ 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; while incomplete, initial experimental results suggest that weights of around 40 g placed at the hook will achieve significantly higher sink rates than 60 g at 3.5 m. The exact amount of weight would have to be determined experimentally.

Advice to management

The research described above and experience in Australia's ETBF underline the importance of using weights to achieve initial and final sink rates that will significantly reduce the risks to seabirds from baited hooks. Factors affecting the sink rate include distance of the weight from the hook, the amount of weight used and whether the bait is live or dead.

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, fisheries managers should consider prohibiting the use of live bait to limit potential impacts on seabirds, especially at times of high seabird abundance, or only permit its use with other additional measures that offset the higher risk of seabird bycatch.

Currently available additional measures include night setting, heavier weights, weights placed closer to the hook and area or seasonal closures. However, in addition to research currently underway to improve existing mitigation measures, there are also several new mitigation techniques under development which are likely to be available to fishers in the next year and may offer considerable potential to reduce seabird bycatch. These include a device to set hooks underwater, below the propeller turbulence, at a depth of ≥ 4 metres and a re-usable bait pod. The bait pod comprises a casing containing a 60 g weight which encases the hook tip during setting – placing the weight at the hook to maximise sink rate – and which swings clear of the bait once a pre-set depth is achieved.

With dead bait, the small changes to swivel weights and leader lengths typically preferred by industry are unlikely be detectable 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 to 4 m from hooks include in assessments gear configured with 120 g swivels ≤ 2 m from hooks and gear with a smaller amount of weight placed at the hook. Research along these lines is presently underway in Australia, including on the use of weights of < 60 g placed at the hook, which are likely to achieve significantly higher sink rates than weights placed 3 to 4 metres away from the hook. This research will include assessing the impact on target catch rates. Australia aims to submit the results of this research to the IOTC in 2011.

It is suggested that the results of this continuing research and development be reviewed at the IOTC WPEB and Scientific Committee meetings in 2011 and the line weighting and other relevant aspects of Resolution 10/06 be revised as appropriate.

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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 1.

Table 1. Mean (\pm 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)			Final sink rate (m/s)		
		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

The addition of a TDR to yellow-tail mackerel with a 60 g swivel slowed the initial sink rates by, on average, 0.01 m/s. 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 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 x 1.0 cm, 7 g, neutrally buoyant) affected the sink rates of hooks baited with squid, a 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 were 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 (ie., 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 2. Since there was no discernible difference in sink rates associated with presence or absence of a light 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 2. Mean (\pm s.d.) sink rates (initial and final) of baited hooks with and without light sticks.

Initial sink rate (m/s)		Final sink rate (m/s)	
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 $\log(\text{Depth}+1)$ 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 1 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 1.

Table 1. 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.

