SBWG-3 Doc 05 Rev 1
Agenda Item 1, 2

Agreement on the Conservation of Albatrosses and Petrels

Third Meeting of the Seabird Bycatch Working Group

Mar del Plata, Argentina, 8 – 9 April 2010

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

Graham Robertson*, Steven G. Candy, Barbara Wienecke & Kieran Lawton

Australia

Experimental determinations of factors affecting the sink rates of baited hooks to minimise 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

* Corresponding author at: Australian Antarctic Division, Channel Highway, Kingston, Tasmania 7050, Australia. Tel: +61 3 62 323 337; fax: +61 3 62 323 449
E-mail address: graham.robertson@aad.gov.au (G. Robertson).

ABSTRACT

An experiment was conducted in Australia's pelagic longline fishery to establish a scientific basis for the introduction of line weighting regimes into the fishery 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. There were no detectable differences in sink rates between different species of bait within the same bait life status group. On average, live bait sank much slower than dead bait, greatly increasing the exposure of baited hooks to seabirds. 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. Within the dead bait group, 60 g and 100 g swivels with the same leader lengths 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 and failed to attain 6 m depth after 18 seconds. Initial sink rates (0-2 m) were increased by placing swivels close to hooks and final rates (> 4 m) by increasing the weight of the swivels. The results indicate that the small (incremental) changes to swivel weights and leader lengths typically preferred by industry will not reduce seabird mortality, because resultant increases in sink rates will be insubstantial. Changing line weighting regimes to reduce seabird mortality requires consideration of not only cumulative sink rates to target depths but the sink rates near the surface. We suggest that to reduce seabird mortality compared to that associated with 60 g swivels and ~3.5 m leaders (the preferred option by industry) requires branch lines be configured with swivels ≥ 120 g ≤ 2 m from hooks.

Keywords: Pelagic longline fisheries; Sink rates; Line weighting; Bait species; Bait life status; Seabird conservation; Co-operative research

1. 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 samples 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., 2008) 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 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 of threatened species (Baker and Wise, 2005), which at the time exceeded the standard permitted by legislation (<0.05 birds/1000 hooks; Threat Abatement Plan, 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 to Australia's (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) based on the results of the experiment, provide advice to management on line weighting regimes to trial in the fishery to minimise 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.

2. Materials and methods

2.1. Characterising sink profiles/rates

The sink profiles/rates of baited hooks depend on where they are deployed in relation to propeller turbulence, whether branch lines contain added weight, such as leaded swivels, and the proximity of weight to the hook. Typically, both weighted and unweighted branch lines set directly into propeller turbulence or on the edge of vessel wake sink in two-stages (Figure 1). The first stage occurs immediately on deployment when baited hooks are held aloft in propeller turbulence and sink relatively slowly. The second stage occurs when gear clears turbulent water and sinks with a linear (i.e., constant) profile - and much faster - to target depths. These two stages are also evident if weighted lines are deployed into non-turbulent water. In this case the proximity of leaded swivels to the baited hook influences the shape of the profiles. 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, exerting maximum pull-down, resulting in much faster sink rates. Branch lines without leaded swivels (or no equivalent point source of weight) deployed into non-turbulent water tend not to sink with the same two-stage profile. Instead they sink with a near-linear profile from the surface (e.g., Melvin, et al., 2009). 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 period baited hooks are near the surface and thus most visible and assessable 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.

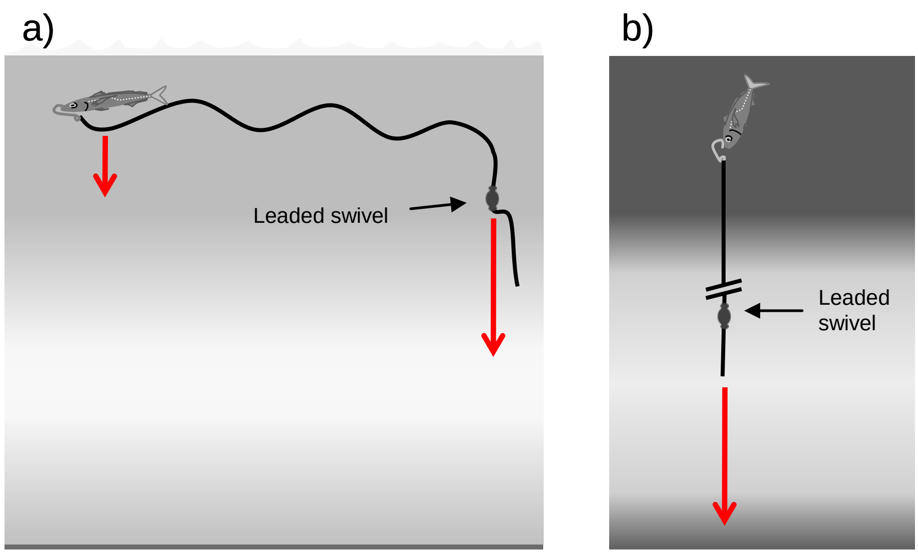

Figure 1. The source of the difference between the initial (part ‘a’) and final (part ‘b’) stages of line sinking. Landed baits sink slower than the leaded swivel until the length

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 swivel weight.

2.2. 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.

2.3. Line weighting experiment

2.3.1. Fishing vessel, location and gear

The experiment was conducted on the F/V *Assassin*, 12 nm east of Forster (32º 13'S; 152º 32'E), NSW, Australia, from 15-17 April 2005. In 2005 there were 208 permit holders in the ETBF, although not all were active (source: the Australian Fisheries Management Authority [AFMA]). 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. At vessel setting speed (8 knots, 4.1 m/s) the engine ran at 1,300 rpm and the propeller at ~ 440 rpm. 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, in press) 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 single 60 g, single 100 g or a combination 160 g (60 g and 100 g swivels crimped together 8 cm apart; single 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. The live fish were caught at sea the day before the experiment commenced and retained in purpose built tanks on the vessel. 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 (Figure 2). The sea state was calm (wave height < 1.0 m) on all days of the experiment and wind was variable to 10 knots.

Figure 2. Bait species used in the experiment showing comparative size differences, hook size and hooking position for the live fish bait deployment. Dead fish baits were hooked at the base of the head.

2.3.2. 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 3). Hooking position (see above) was not included as a factor because live bait is always hooked through the back and dead bait is always hooked through either the head or tail. 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 use on each set, each with a TDR attached. To minimise/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. Thus any variation in setting conditions between or within days (e.g., change in sea state or current directions) would have the effect of increasing the size of the variances around the estimates, rather than confounding comparisons on mean sink rate. 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.

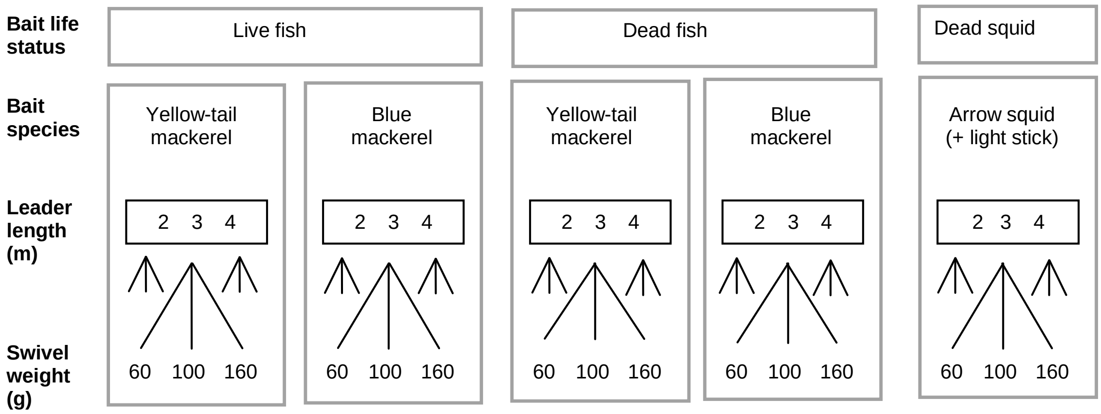

Figure 3. Experimental design showing the hierarchical order of factors testing for the effects of bait life status, bait species, leader lengths and swivel weights on the sink rates of baited hooks. The figure has been simplified for clarity. The boxes around bait species highlight the absence of live 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.

2.3.3. 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 not to have affected the sink rates (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, the water entry time (from the digital watch) noted in the time–depth files and the median zero offset value determined from the 10 rows of data before the water entry time. This value was then used to ‘correct’ the depth readings of the TDRs.

2.3.4. Line casting procedure

To ensure the mainline was not dragged at the start of each set, which would impede sinking (Robertson, et al., in press), 700 metres 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. The layout for line setting operations is shown in Figure 4. 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 branch line casting procedure was typical for the fishery. 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 (Figure 4). The clip end of the branch line was then attached to the mainline without delay.

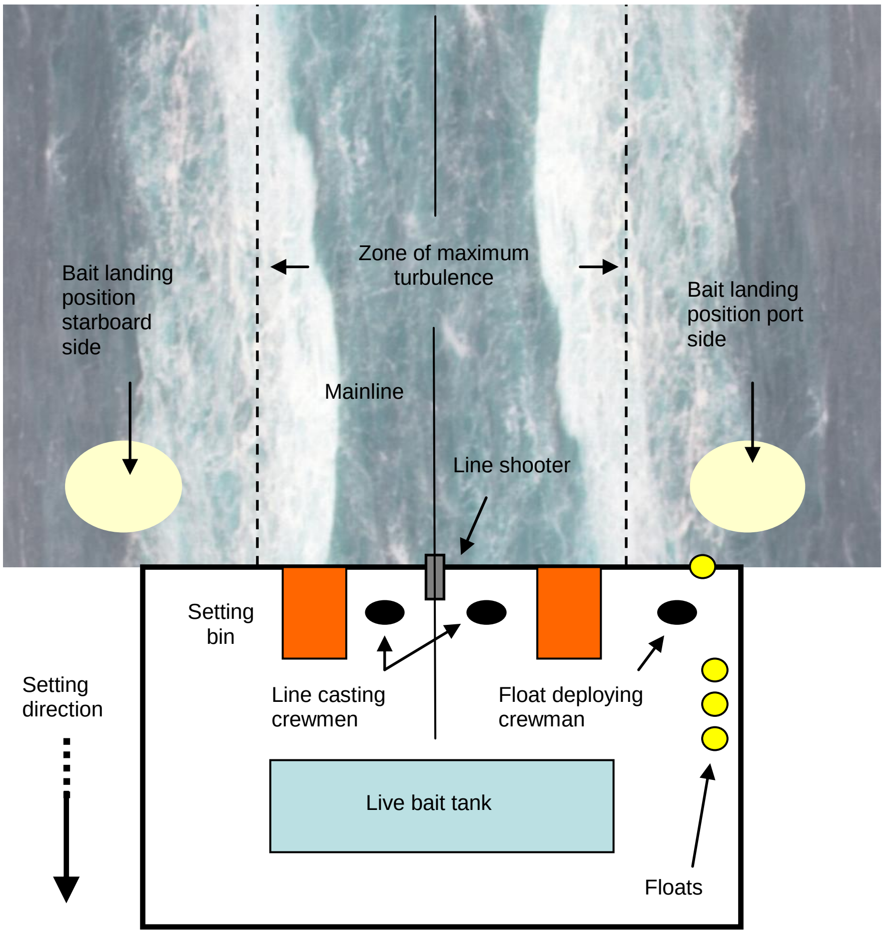

Figure 4. Line casting set-up and bait landing positions in relation to the main area affected by propeller turbulence.

2.3.5. Data analysis

Sink profiles were analysed for depth to times from water entry until 18 seconds later, in 1 second intervals. This depth range and associated elapsed time were 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 further comparisons between the various effects. 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. The depth range assessed provided approximations of both the initial and final phases of sink profiles described above, which were taken to be the 0-2 m and the 4-6 m depth ranges, respectively. In addition to the analysis to 18 seconds, data for live bait (but not dead bait; see below) was assessed up to 120 seconds after deployment to determine if baits had reached target depths.

The data was analysed using linear mixed models as described in Robertson et al. (2008). The zero depth:zero time data points were excluded from the analysis because they have zero variance. Fixed effects in the LMM were bait life status, bait species, leader length, swivel weight. The crew of the *Assassin* deployed branchlines on both sides of the vessel which necessitated the inclusion if 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). 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. In the non-parametric form of the LMM, ‘time’ was included as a factor with 18 levels (i.e. times 1-18 s in 1 s intervals) to examine the depth trend with time without smoothing using cubic splines. Significance of fixed effects was judged using sequential Wald statistics (Welham and Thompson, 1997). In the parametric form of the LMM, time was fitted as a linear trend along with smoothed random deviations where the sum of linear and random deviation terms corresponds to fitting a cubic smoothing spline (Verbyla *et al*., 1999). This allowed nonlinear interpolation between time points and the prediction of time to nominal depth (Welham *et al*. 2004). The parametric (cubic spline) LMM gives predictions that “gain strength” from considering entire depth profiles as a sequence of related values, rather than simply a set of time-specific means as with the non-parametric LMM. The non-parametric LMM was used to validate the parametric LMM to determine if the combined linear and cubic spline terms adequately modelled the trend in the predicted means. 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(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). The correlation between time points separated by x time units is given by the estimated autocorrelation parameter to the power of x. This model corresponds to that of Diggle et al. (2001) with experimental sink profiles as random effects plus residual variance with autocorrelation but no measurement error. 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 seconds were predicted using the parametric LMM to search across time at 0.1 second 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 treatments or each combination of treatment with one or other of the other fixed effect factors were obtained as $2\sqrt{2}SE(\hat{y})\,\exp(\hat{y}) - 1$, where $\hat{y}$ was averaged across factor means used in pair-wise (i.e. overlaid) graphical comparisons. 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. The method for interpreting the confidence bounds is given in Appendix B.

3. 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. As mentioned previously it was not possible to analyse all data combined because of the lack of balance in the design due to the non-existence of live squid bait. Thus data for fish baits (both life forms) and dead baits (all three species) were analysed separately.

3.1. 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.

3.2. Fish baits (live versus dead)

There was no detectible difference in sink rates between yellow-tail mackerel and blue mackerel baits within the same bait life status (P>0.1 for both comparisons), so bait species was excluded to simplify the analysis. Swivel weight had a significant effect on sink rates suggesting that, overall, the heavier the weight the faster the sink rate (Table 1). There was a significant interaction between bait life status and leader length. The source of the interaction is the contrast between the sink profiles of the 4 m leader and the 2 m and 3 m leaders (Figure 5): dead fish baits on 2 m and 3 m leaders sank on average considerably faster than their live counterparts irrespective of swivel weight, but with the 4 m leaders there was either virtually no difference between sink profiles (100 g swivels) or the difference was evident only in the last several seconds of the profiles (60 g and 160 g swivels). On average, after 18 seconds elapsed time most swivel weight/leader combinations for dead fish were appreciably deeper than their live fish counterparts. The difference between dead and live bait was greatest for the 2 m leaders and least for the 4 m leaders. All but two of the nine combinations for live fish bait had not reached 4 m depth whereas most combinations of dead bait were at least 2 m deeper than live bait. The contrast between dead and live fish was most evident in the 160 g x 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 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.

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

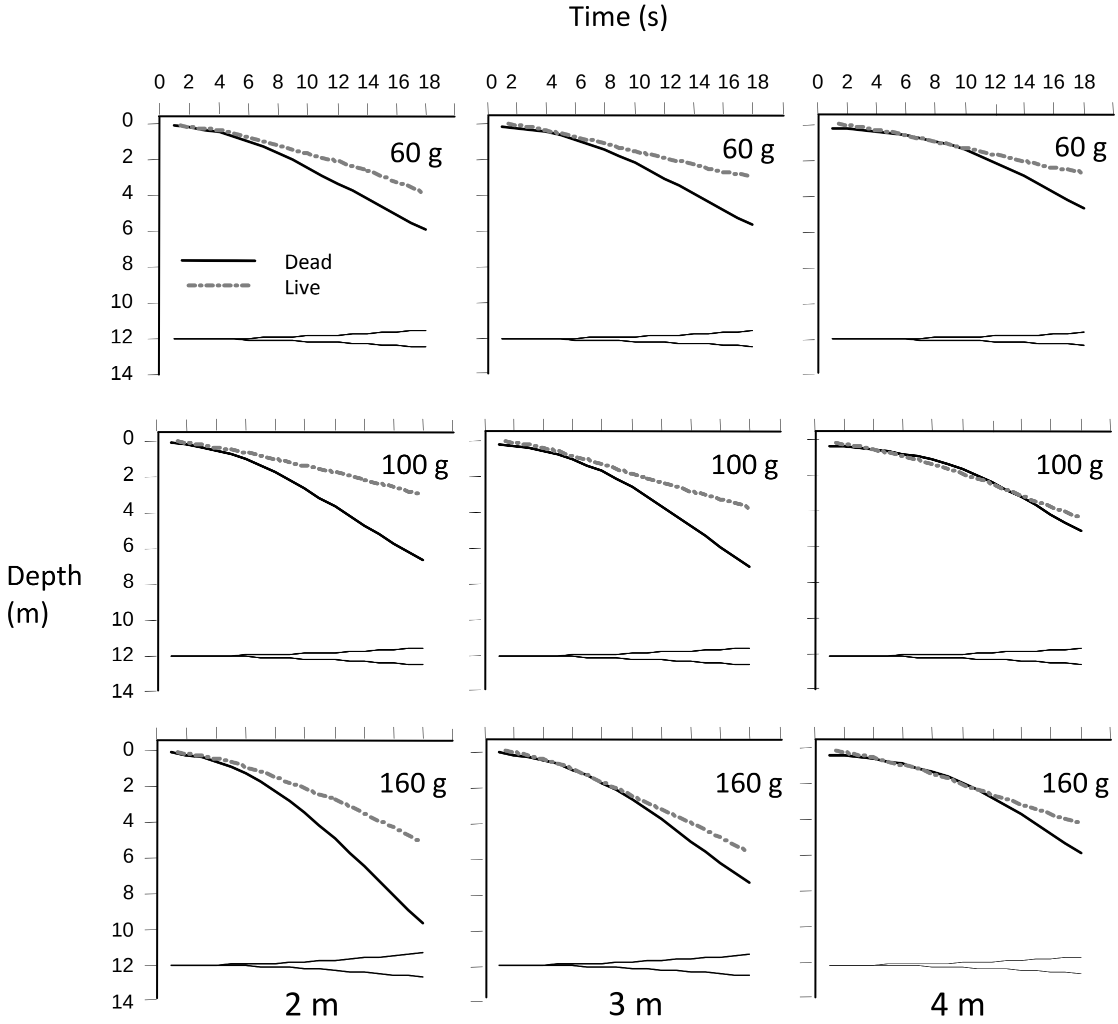

Figure 5. Mean sink profiles of dead and live yellow-tail mackerel and blue mackerel bait in relation to swivel weight and leader lengths in the first 18 seconds after deployment. Data for both fish species have been averaged (see text and Table 1). n = 22 for each swivel weight x leader length combination

Individual sink profiles of live fish bait (Figure 6) were much more variable than dead fish bait (Figure 7). Analysis of sink profiles for live blue mackerel bait to 120 seconds 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). After 120 seconds many individual live baits were still < 10 m beneath the surface. Comparable data for individual dead baits are not presented because at the 18 seconds 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.

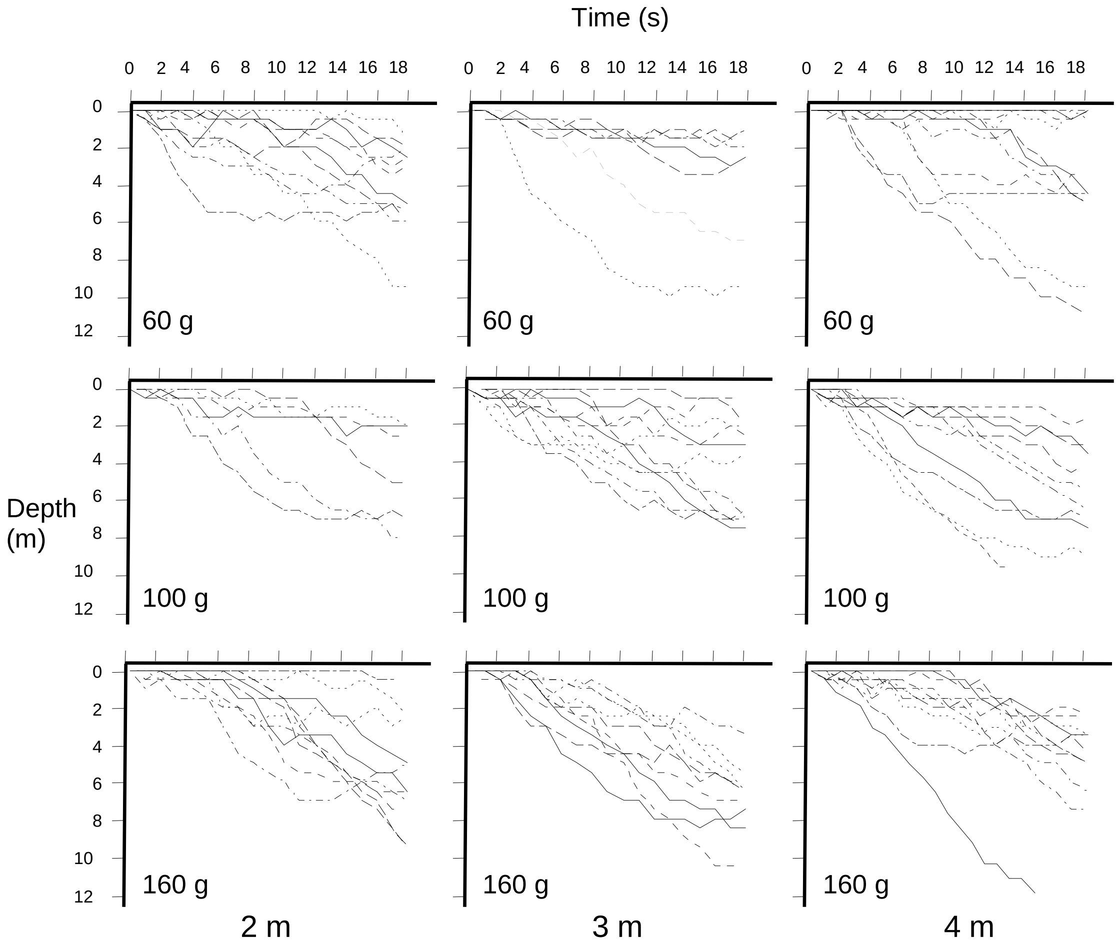

Figure 6. Sink profiles of individual live blue mackerel bait as a function of swivel weight and leader length in the first 18 seconds after deployment (corresponds to 0-6 m depth).

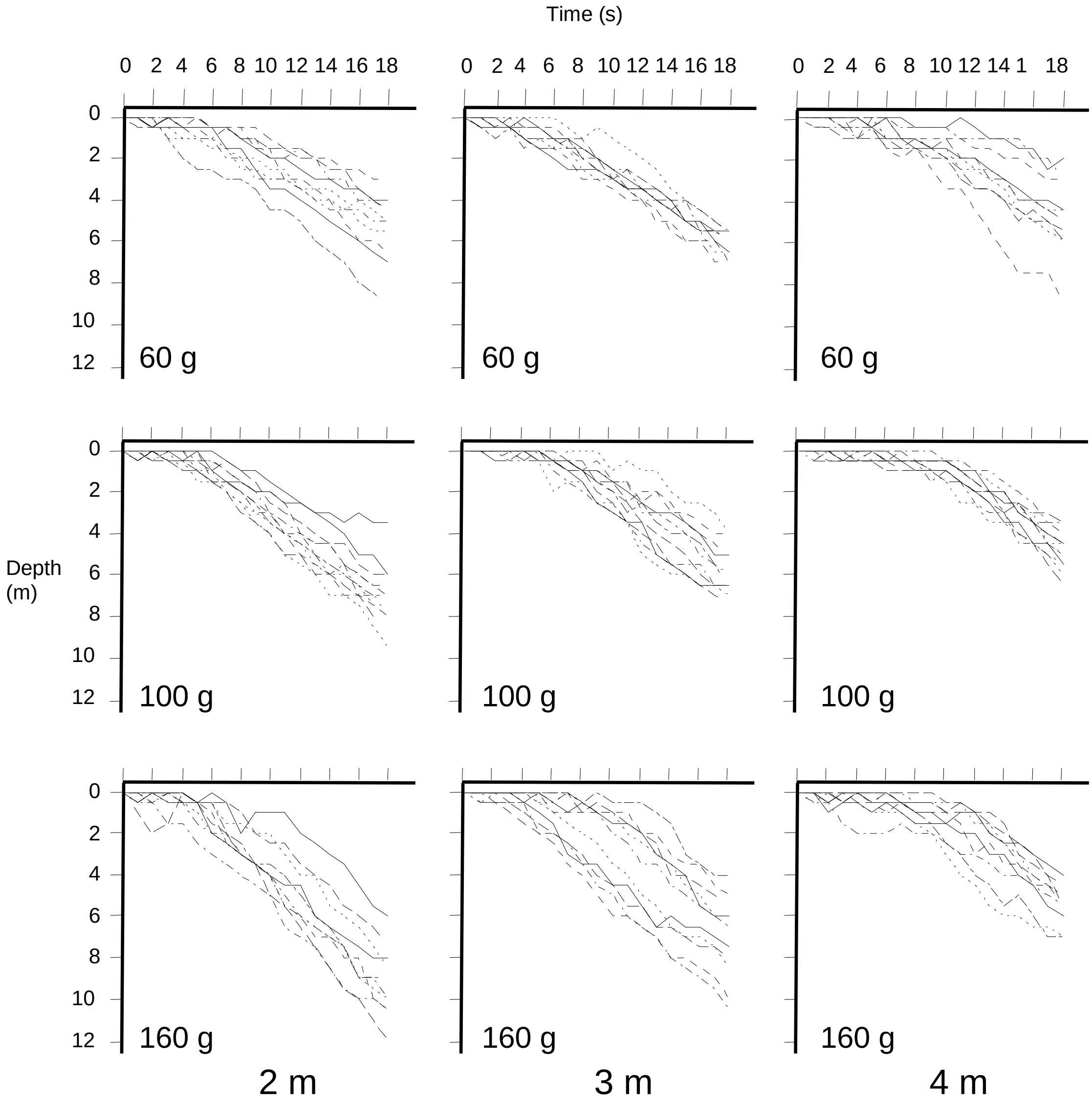

Figure 7. Sink profiles of individual dead blue mackerel bait as a function of swivel weight and leader length in the first 18 seconds after deployment (corresponds to 0-6 m depth).

3.3. Dead baits (fish and squid)

The analysis for dead baits includes both species of fish and squid. As with the fish baits alone, the inclusion of squid made no 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 8, which presents the results in two forms - leader length as a function of swivel weight and swivel weight as a function of leader length. Both alternatives are presented to accommodate members of industry (and fisheries management agencies) who will embrace requirements to increase swivel weights but not shorter leaders, and vice versa (the cost of changing swivels greatly exceeds that of changing leader lengths). Within the same swivel weight, sink profiles for the 60 g and 100 g swivels and 2 m and 3 m leaders were almost identical and both were significantly faster than 4 m leaders (i.e., sink rates increased as leader length decreased from 4-3 m but not from 3-2 m). In contrast the sink profiles for all three leaders with 160 g swivels were significantly different. After 18 seconds elapsed time the 160 g x 2 m combination exceeded 10 m depth, twice that of the 160 g x 4 m combination. Within leader length, the sink profiles of the three swivel weights for both 3 m and 4 m leaders were statistically inseparable as were the 60 g and 100 g swivels with 2 m leaders. Gear with 2 m leaders and 160 g swivels sank significantly faster than the two lighter swivels on 2 m leaders.

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.

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

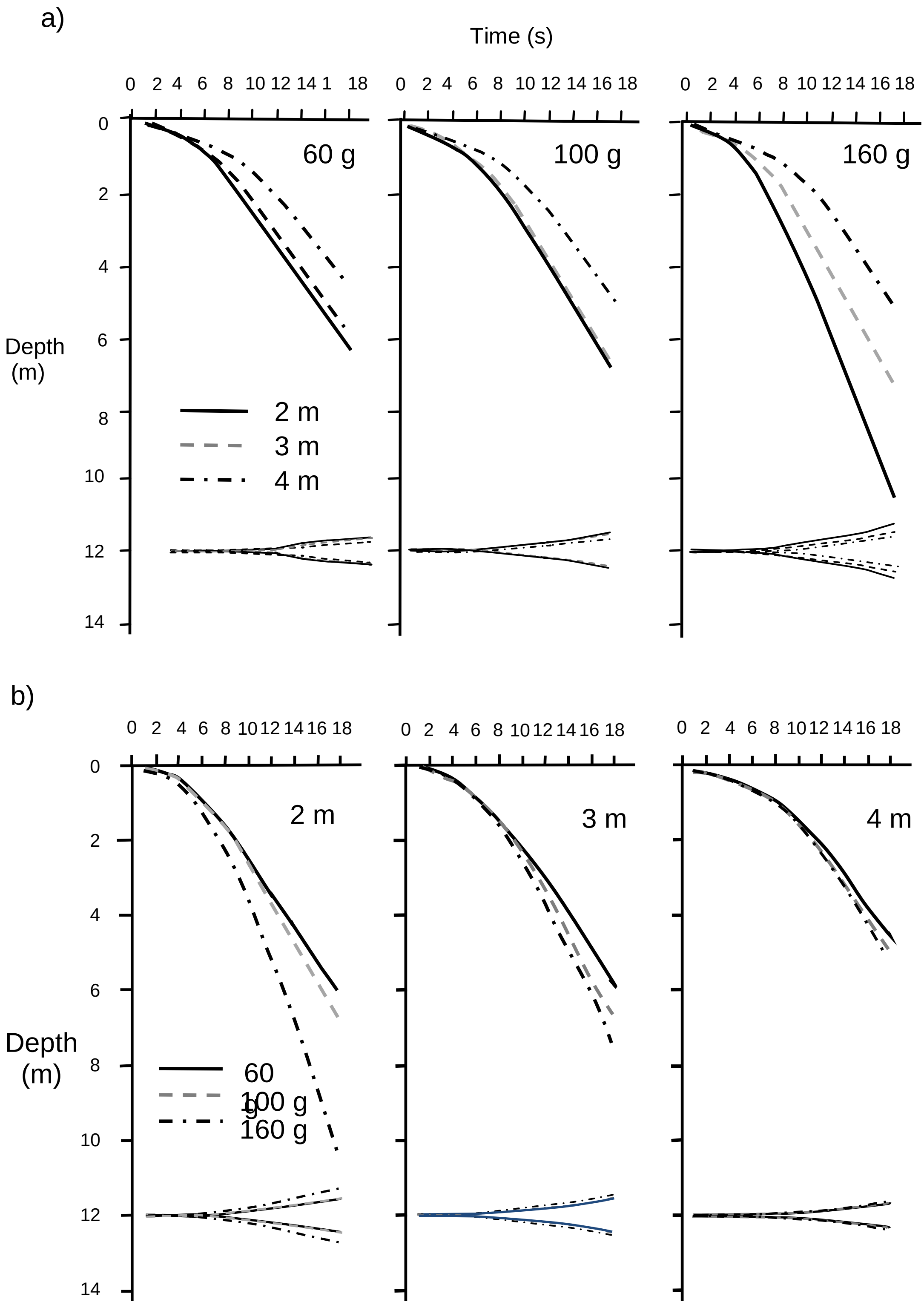

Figure 8. Mean sink profiles for the three species of dead baits (yellow-tail mackerel, blue mackerel and squid) in the first 18 seconds after deployment. The data are presented as: a) leader length as a function of swivel weight and b) swivel weight as a function of leader length. Data for the three bait species have been averaged (n = 33 for each combination).

3.4. Sink rates

3.4.1 Live bait

The mean sink times and rates for all combinations of swivel weight and leader length are shown in Table 3. In the table the time axis has been extended from 18 seconds to 20 seconds to increase the number of combinations that reached 6 m depth. All leader length combinations with 60 g and 100 g swivels failed to reach 6 m depth after 20 seconds. Mean cumulative rates (0-6 m) for the three leader lengths with 160 g swivels varied from 0.30-0.33 m/s. Mean initial rates (0-2 m) ranged between 0.15 m/s (60 g x 2 m) and 0.23 m/s (160 g x 3 m). As mentioned, on average only live baits attached to 160 g swivels reached 6 m after 20 seconds. Final sink rates for 160 g swivels ranged from 0.42-0.47 m/s.

3.4.2 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. The fastest mean cumulative rate (0.45 m/s) was the 160 g x 2 m combination and the 60 g x 4 m combination the slowest. Mean initial sink rates ranged from 0.18-0.27 m/s and mean final rates ranged from 0.48 (60 g x 2 m) - 0.74 (160 g x 2 m) m/s, 2-3 times faster than initial rates. With respect to final rates (4-6 m), the estimates in Table 3 for 4 m leaders (100 g and 160 g swivels) will be slower than actual rates because leaders of this length would not be taut by 4 m depth and gear would still be accelerating. Final rates for gear with 4 m leaders should be similar to those for 2 m leaders (ie., 0.74 m/s for the 160 g x 4 m combination). Within each swivel weight mean initial rates were inversely proportional to leader length (the shorter the leaders the faster the sink rate). In general, mean final sink rates for dead baits increased as leader length decreased, with the trend being strongest for the 160 g swivels.

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 rage (≤ 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). *after 20 seconds had not reached maximum depth in range. Estimates of the variances (95% c.l.'s) are presented in Figures 4 and 7. **likely still accelerating (see text).

Life	Swivel	Leader	Mean sink time (s)			Mean sink rate (m/s)		
status	wgt. (g)	length (m)	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	0.23	0.48
Live	60	2	*	13.4	*	*	0.15	*
Dead	60	3	19.1	9.5	4.2	0.31	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	0.23	0.50
Live	100	2	*	12.2	*	*	0.16	*
Dead	100	3	17.6	9.2	4.2	0.34	0.22	0.49
Live	100	3	*	10.4	*	*	0.19	*
Dead	100	4	19.1	11.0	4.3	0.31	0.18	0.46**
Live	100	4	*	11.0	*	*	0.18	*
Dead	160	2	13.4	7.4	2.7	0.45	0.27	0.74
Live	160	2	19.7	8.9	4.2	0.30	0.22	0.48
Dead	160	3	15.8	8.3	3.6	0.38	0.24	0.59**
Live	160	3	18.2	8.6	4.8	0.33	0.23	0.42
Dead	160	4	19.7	11.0	3.6	0.30	0.18	0.54**
Live	160	4	20.0	9.8	4.2	0.30	0.19	0.47

4. Discussion

4.1. Choice of factors and levels

An important consideration with these kinds of experiments is that the factors assessed produce contrasting responses within a reasonable number of replicates. Another is that the recommendations arising from the research must be practical from a fishing operations perspective and, ultimately, be effective in deterring seabirds. Both considerations influenced the design of the experiment, the choice of combinations being a compromise between what was tolerable to the fishing industry and desirable in terms of improving understanding of the relationships between the various effects examined. The three species of bait and the live and dead forms of fish bait were chosen because they covered virtually all the bait options used in the fishery. At the time of the experiment branch lines comprised either no added weight (for the purposes of sinking the line) or, in the case of live bait users, a small (9 g) box swivel several metres from the hook. The three levels of swivel weights and the three leader lengths were chosen to try to detect trends, which would be important in the selection of a line weighting regime for the fishery and in the design of a later seabird deterrent experiment, if required. The 1 m increments in leader length and the 40 g difference between 60 g and 100 g swivels, though small, accommodated industry concerns that weight close to hooks may reduce fish catch (to fishermen these small differences were substantial). The 160 g combination swivels, which are not commercially available, were included in case the difference between the two lighter swivels proved difficult to detect, which turned out to be the case. Also, in pelagic longline fisheries interacting with *Procellaria* sp. petrels and *Puffinus* sp. shearwaters - which are among the most difficult species to deter - it is likely that heavy swivels and short leader lengths will be required to substantially reduce mortality.

In terms of international relevance, the results for live bait are mainly relevant to Australia but will be important should live bait be considered by other nations. 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). With respect to the other factors, the bait species used were similar in size and weight to those adopted in many other coastal pelagic longline fisheries in the world and the 60 g swivel weight fell within the range for other countries (45-80 g; source: ACAP 2007). The 100 g and 160 g swivels were unique to the experiment. The leader lengths were similar to those used in other coastal longline fisheries in the southern hemisphere (2-4 m commonest; source: ACAP 2007).

4.1. 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. The final sink rates of the same three species in the static trial described in Appendix A differed significantly ($p<0.001$ for all comparisons) with the smallest bait (yellow–tail mackerel) sinking fastest and the largest (squid) sinking slowest (G. Robertson, unpublished data). 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 the effect of bait species was minor and overridden in importance by the other effects examined.

4.3. 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 and 120 seconds time periods.

The statistical interaction between bait life status and leader length means the latter cannot be considered in isolation of the former. The relationship between these two effects differs with the 4 m leaders compared to the 2 m and 3 m leaders. Mean live versus dead bait sink profiles of the latter two leader lengths (all swivel weights) differed markedly, but mean 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, as revealed by the 4 m leaders for 100 g and 160 g swivels and the 3m leader and 160 g swivel in Figure 5. There could be two reasons for this – live bait sinks faster, on average, on long leaders or dead bait sinks slower on long leaders (or elements of both). There is a logical reason why live bait might sink faster on long leaders. Underwater observations off a stationary fishing vessel suggests leader length influences the swimming behaviour of bait (G. Robertson, personal observations). The natural tendency of live yellow-tail mackerel was to dive away from the surface. When leaders became taut the swivel dragged on the fish, causing it to struggle, which impeded sinking. Four metre leaders take longer than 2 m leaders to become taut, providing more time for fish to dive before being pulled by the swivel.

Nonetheless, there is little evidence in Figure 5 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. The likely reason for this is that the branch lines observed underwater were thrown with some degree of 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 among all swivel weight and leader length combinations. Also, longer leaders result in slower sink rates for dead bait, which is another reason for the similarity in sink profiles between dead and live bait on 4 m leaders.

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 the most accessible to seabirds. Prior to the experiment there was speculation in the ETBF that live bait would sink faster than dead bait because live fish would swim away from the surface as a defence mechanism. The results to 18 seconds and 120 seconds after deployment show that live baits behave erratically, making generalisations impossible. A small number of individuals did, indeed, sink quickly, exceeding 10 m depth in only 16 seconds (> 0.6 m/s). However, by the 18 second mark the majority had reached less than half that depth and a substantial number 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 second mark, when many baits were < 10 m deep and one bait (60 g x 3 m group) was still within 2 m of the surface.

4.4. Dead bait

The most important findings for the dead bait species were a) the interaction between swivel weight and leader length, based on the data for the overall sink profiles in Figure 8, and b) the influence of these effects on the initial and final sink rates.

The inconsistency in the swivel weight/leader length relationship pertains to the average profiles for 2 m and 3 m leaders within 60 g and 100 g swivels, which were virtually identical, compared to profiles for all three leader lengths within 160 g weights, which differed markedly. Shortening leaders from 4-3 m on gear with 60 g and 100 g swivels significantly increased sink rates, but shortening from 3-2 m made no difference through the recorded range. In contrast, within the 160 g swivels each 1 m reduction in leader length significantly increased the sink rate. Expressed the other way (swivel weight as a function of leader length) within both 3 m and 4 m leaders simply adding weight to swivels (in the 60-160 g range) made no difference to the shape of the sink profiles. Within 2 m leaders, adding 40 g to the weight of a 60 g swivel (to make 100 g) made no difference to the sink profiles. Sink profiles improved markedly with 160 g swivels on gear with 2 m leaders.

In summary, if priority is given to swivel weight the sink profiles of gear with 60 g and 100 g swivels can be improved by shortening the leaders from 4-3 m but not from 3-2 m. Improvement from 3-2 m requires the use of 160 g swivels. This is because of the faster initial sink rate of 160 g swivels. Leaders with these swivel weights become taut more quickly than gear with the two lighter swivels. If priority is given to leader length, adding heavier swivels (in the 60-160 g range) 3 m and 4 m from hooks makes no discernible difference to the sink profiles. This is also the case for 60 g and 100 g swivels 2 m from hooks. To significantly improve sink profiles of gear with 2 m leaders requires the use of 160 g swivels.

As with live bait, the LMM analysis for the dead bait group in Table 2 and the presentation in Figure 8 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 the most seabirds. The initial sink rates (0-2 m; Table 3) show that shortening leaders from 3-2 m results in faster average sink rates. Within 60 g swivels the improvement was, on average, 0.02 m/s compared to 0.05 m/s from 4-3 m (the results for 100 g swivels were similar to those for 60 g). This difference, though small, might be important to seabirds: the reduction from 3-2 m resulted in ~10 % less time that baits are available in the 0-2 m depth range. The comparable results for 160 g swivels are 0.03 m/s and 0.06 m/s for leaders reduced from 3-2 m and from 4-3 m, respectively. Shortening from 3-2 m equates to a ~ 25 % saving in time taken for baits to clear surface waters. Increasing swivel weight while holding leader lengths constant also reduced initial sink rates, but overall the benefits were less than shortening the leaders within swivel weight. In terms of actual initial sink rates, the 160 g and 2 m leader (0.27 m/s) combination sank the fastest and 60 g and 4 m leader (0.16 m/s) the slowest, the former taking 40 % less time to reach 2 m depth than the latter.

All in all, the results for dead bait are what would be expected intuitively: the overall sink profiles (0-6 m) and the initial sink rates most beneficial to seabird conservation can be achieved by placing heavy swivels close to hooks. There is no benefit to the initial sink rate or the entire profiles by increasing swivel weight from 60 g-100 g – the 40 g difference makes no discernible difference. If 60 grams is the basis for comparison, a doubling of this weight should be the starting point in any rationalisation of swivel weights to expedite sink rates. With regard to the leaders, while 2 m leaders do, in fact, improve initial sink rates the proportional improvement tends to decrease with each 1 m reduction in leader length (in the 2-4 m range), suggesting that 1 m leaders may confer little additional advantage over 2 m leaders. 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 the length of the leaders.

5. Implications for seabird conservation

At the time of the experiment weighted branch lines were not required in the ETBF and were not used. In an effort to reduce seabird mortality below the regulated threshold (< 0.05 birds/'000 hooks) AFMA and industry had completed trials involving 38 g, 60 g and 100 g swivels in combination with bird scaring streamer lines. However, the results were inconclusive, partly because of poor compliance levels to weighting and leader length requirements (leaders ranged to 6 m; G. Robertson, personal observations). Insights from the *Assassin* experiment allows speculation on the effect the three weighting regimes on gear sink rates. The 40 g difference between 60 g and 100 g swivels used on the *Assassin* made no discernible difference to the sink rates, either at the surface or deeper down; this would also be expected with the seabird trial. Similarly, the addition of 38 g swivels to unweighted gear, and the 22 g difference between 38 g and 60 g swivels, probably made little difference to sink rates. Increased rates would be expected if weights were placed at the hook, but not 6 m away. Leaders of this length greatly accentuate the time lag at the surface and virtually negate the effect of line weighting.

The implications for seabird conservation regarding live bait are less speculative. The use of live bait in the ETBF is associated with higher seabird by-catch rates (Trebilco, et al., in press). 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 in relatively shallow depths after 120 seconds. At 4.1 m/s setting speed (8 knots) baits would be ~ 74 m and > 490 m astern after these time periods, respectively, and well beyond the area covered by bird scaring streamer lines (the prescribed minimum aerial extent in the ETBF is 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.

6. Implementation in the ETBF

Following on from the experiment, the approach most acceptable to stakeholders was to introduce line weighting into the fishery using the findings from the experiment and assess performance against the seabird conservation standard over time. This enabled industry to continue fishing with weighting regimes they were gaining familiarity with (mainly 60 g swivels), which was an important consideration with respect to achieving uptake in the fishery. Also, it was considered important to proceed with prudence regarding the introduction of change, especially change involving a component of gear (branch lines) critical to the economics of fishing.

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 ≤ 3.5 m from hooks, or 100 g swivels ≤ 4 m from hooks. Baited hooks with these weighting regimes sink at similar rates, but both were permitted out of deference to pro-active 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 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.

7. 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, will require gear be configured with swivels ≥ ~ 120 g ≤ 2 m from hooks. The evidence in support of leaders ≤ 2 m long is clear-cut, that for 120 g swivels less so. However it is neither practical nor economically viable to consider swivels as heavy as 160 g. Gear with 120 g swivels on 2 m leaders would be a reasonable compromise and should sink with a distinctly different profile than gear rigged with 60 g swivels on 3.5 m leaders. We suggest further experimentation involve comparison of baited hooks attached to 60 g swivels on 3.5 m leaders with 120 g swivels on 2 m leaders. An alternative to the latter regime would be to place a smaller amount of weight at the hook. The exact amount of weight would have to be determined experimentally.

8. 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. The evidence for dead bait suggest that increases in sink rates above those associated with 60 g swivels 3-4 m from hooks requires 120 g swivels ≤ 2 m from hooks. This should be considered the minimum weighting regime in future experiments aimed at examining the effectiveness of line weighting regimes in deterring seabirds. Small changes to swivel weights and leader lengths are not detectible at sea and are unlikely to reduce the incidental take of seabirds.

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 summarising 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 and Barry Baker improved a draft.

REFERENCES

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 D.J., Black, A.D., Croxall, J.P., and Parkes, G.B. 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, G.B., and Wise, B.S. 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, T.S., Leite Jr., N.O., Carvalho, D., Sales, G., Furness, R.W., Stein, C.E., Peppes, F.V. Giffoni, B.B., and Monteiro, D.S. 2008. Potential bycatch of seabirds and turtles in hook-and-line fisheries of the Itaipava Fleet, Brazil. Fisheries Research **90**, 217–224.

Dietrich, K. S., Melvin, E. F, 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, P. J., Heagerty, P., Liang, K., and Zeger, S. L., 2001. 'Analysis of Longitudinal Data (2nd ed.)'. Oxford University Press, Oxford.

FAO, (2008). Report of the Expert Consultation on Best Practice Technical Guidelines for IPOA/NPOA–Seabirds. Bergen Norway, 2–5 September 2008. FAO Fisheries and Aquaculture Report. No. 880, Rome, FAO. 37p.

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

Gilmour, R. A., Thompson, R., and Cullis, B. R. 1995. Average information REML: An efficient algorithm for variance parameter estimation in linear mixed models. Biometrics **51**, 1440-1450.

Gilmour, R. A., Cullis, B. R., Welham, S. J., and Thompson, R. 1999. Asreml Reference Manual. Biometric Bulletin No. 3. (Orange Agricultural Institute, Orange, NSW Australia).

Jiménez, S., Domingo, A., Brazeiro, A. 2008. Seabird bycatch in the Southwest Atlantic: interaction with the Uruguayan pelagic longline fishery. Polar Biology **32**, 187–196.

Melvin, E. F. and 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, E. F., 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). Pp19.

Moreno, C. A., Castro, R., Mújica, L. J., 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, S. L., Nel, D. C., Ryan, P. G., and Underhill, L.G. 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., McNeill, M., Smith, N., Wienecke, B., Candy, S., and 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, C. A., Crujeiras, J., Wienecke, B., Gandini P., McPherson, G., and Seco Pon, J. P. 2008. 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., C.A. Moreno, E. Gutiérrez, S.G. Candy, E.F. Melvin and J.P. Seco Pon. 2008. Line weights of constant mass (and sink rates) for Spanish system Patagonian toothfish longline vessels. CCAMLR Science, 15: 93–106.

Robertson, G., Candy, S. G., and Wienecke, B. (in press). Effect of line shooter and mainline tension on the sink rates of pelagic longlines and implications for seabird interactions. Aquatic Conservation: Marine and Freshwater Ecosystem.

Rodriguez-Marin E., Arrizabalaga H., Ortiz M., Rodriguez- Cabello C., Moreno G. and Kell L.T. 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.

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. pp 30.

Trebilco, R., Gales, R., Lawrence, E., Alderman., Robertson, G., and Baker, G. B. (in press, 2010). Seabird bycatch in the Eastern Australian Tuna and Billfish pelagic longline fishery: temporal, spatial and biological influences. Aquatic Conservation: Marine and Freshwater Ecosystems.

Verbyla, A. P., Cullis, B. R., Kenward, M. G., and Welham, S. J. (1999). The analysis of designed experiments and longitudinal data using smoothing splines (with discussion). *Applied Statistics* **48**, 269–311.

Waugh, S. M., MacKenzie, D. I., and Fletcher, D. (2008). Seabird bycatch in New Zealand trawl and longline fisheries, 1998–2004. *Papers and Proceedings of the Royal Society of Tasmania, Volume 14*: 45-66.

Welham, S. J., and Thompson, R. (1997). Likelihood Ratio Tests for Fixed Model Terms Using Residual Maximum Likelihood. *Journal of the Royal Statistical Society*, *Series B (Methodologial)*. **59**, 701-714.

Welham, S. J., Cullis, B. R., Gogel, B., Gilmour, A., and Thompson, R. (1997). Prediction in linear mixed models. *Australian and New Zealand Journal of Statistics* **46**, 325-347.

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 seconds 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 leader. The results are shown in Table 1.

Table 1. Mean (± s.d.) sink rates (initial and final) for yellow-tail mackerel (YTM) and blue mackerel (BM) and 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
YTM	100	0.50 (0.02)	0.49 (0.01)	0.18	0.96 (0.02)	0.94 (0.07)	0.44
YTM	150	0.58 (0.02)	0.57 (0.01)	0.11	1.18 (0.03)	1.14 (0.05)	0.001
BM	60	0.39 (0.01)	0.41 (0.01)	0.006	0.77 (0.04)	0.77 (0.03)	0.97
BM	100	0.47 (0.01)	0.49 (0.01)	0.001	0.90 (0.05)	0.93 (0.02)	0.18
BM	150	0.56 (0.01)	0.56 (0.01)	1.00	1.10 (0.04)	1.06 (0.04)	0.02

Five of the comparisons overall were statistically significant at the P < 0.01 level. However, this reflects not only differences between weights but the precision (as indicated by the small standard deviations proportional to the means) attained under the controlled conditions in the tank. More relevant is the actual difference between the means. Initial rates were either not affected by the addition of a TDR (three of the six comparisons) or slowed by up to 0.02 m/second. Final mean sink rates for the 60 g and 100 g swivels were not affected by the addition of a TDR but the addition of a TDR to the 150 g swivels increased mean final rates by ≤ 0.04 m/second. This result is surprising because it contradicts those for the 60 g and 100 g swivels. It is somewhat similar to the effect of a TDR on an unweighted version of the yellow-tail mackerel bait (increased by 0.06 m/s; G. Robertson, unpublished data). The logical expectation would be as for the results for the two lighter swivels – either no discernible TDR effect or a slight slowing of sinking. We have no plausible explanation for this inconsistency. Baits deployed at sea are most vulnerable to attack by seabirds when at or near the surface, so with the tank trial it is appropriate that priority be given to the initial sink rates. We conclude that TDR effects on initial sink rates of all swivel weights were either not discernible or slight, and that effects on final rates were either non-existent (60 g and 100 g swivels) or minor (150 g).

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 (± 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.

Explanation of confidence bounds

If differences between average profiles for a given time are greater than the bounds then the difference can be considered significant at the 95% level. Since these confidence bounds are determined by multiplying the standard error of the predicted mean depth at a given time on the log scale by the predicted mean depth, the bounds will depend on which set of predicted mean depths have been used therefore the bounds for each level of the factor are shown. Comparison between pairs of factor levels should use the average of the bounds relevant to the comparison.

Models of error structure

As in Robertson *et al*. (2008), 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 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 seconds after deployment.