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Effect of line shooter and mainline tension on the sink rates of pelagic longlines and implications for seabird interactions

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ABSTRACT

1. The likelihood that seabirds will be hooked and drowned in longline fisheries increases when baited hooks sink slowly. Fishermen target different fishing depths by setting the mainline through a line shooter, which controls the tension (or slackness) in the line. An experiment was conducted in Australia's pelagic longline fishery to test the hypothesis of no difference in sink rates of baited hooks attached to mainline set under varying degrees of tension.

2. Mainline was set in three configurations typically used in the fishery: (a) surface set tight with no slackness astern; (b) surface set loose with 2 s of slack astern; and (c) deep set loose with 7 s of slack astern.

3. Tension on the mainline had a powerful effect on sink rates. Baited hooks on branch lines attached to tight mainlines reached 2 m depth nearly twice as fast as those on the two loose mainline tensions, averaging 5.8 s ($0.35\,\mathrm{m\,s^{-1}}$) compared with 9.9 s ($0.20\,\mathrm{m\,s^{-1}}$) and 11.0 s ($0.18\,\mathrm{m\,s^{-1}}$) for surface set loose and deep set loose tensions, respectively.

4. The likely reason for the difference is propeller turbulence. Tight mainline entered the water aft of the area affected by turbulence whereas the two loose mainlines and the clip ends of branch lines were set directly into it about 1 m astern of the vessel. The turbulence presumably slowed the sink rates of baited hooks at the other end of the branch lines.

5. The results suggest that mainline deployed with a line shooter (as in deep setting) into propeller turbulence at the vessel stern slows the sink rates of baited hooks, potentially increasing their availability to seabirds. Unless mainline can be set to avoid propeller turbulence the use of line shooters for deep setting should not be promoted as an effective deterrent to seabirds. Copyright © 2010 John Wiley & Sons, Ltd.

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KEY WORDS: pelagic longline fisheries; mainline tension; line shooter; seabird interactions; co-operative research

INTRODUCTION

Seabirds are killed incidentally in pelagic longline fisheries throughout the southern hemisphere (Baker and Wise, 2005; Bugoni *et al.*, 2008; Jiménez *et al.*, 2008; Petersen *et al.*, 2008). The majority of fatal interactions occur when lines are being set when seabirds become hooked or entangled in gear and drown. Evidence from demersal longline fisheries indicates that increasing the sink rate of baited hooks substantially reduces seabird mortality (Agnew *et al.*, 2000; Robertson *et al.*, 2006). These studies reveal that risks to seabirds can be minimized if baited hooks not only sink quickly but commence sinking immediately upon deployment. Short surface times reduce the visual stimuli to seabirds, the availability of sinking baits and the chances of fatal interactions occurring. Although demersal and pelagic longlines differ, the same rationale about fast initial sink rates should also apply to pelagic longline fisheries. In pelagic longline fisheries sink rates are influenced by a range of gear-related and operational factors, some of which are well known and some that are poorly understood.

One factor about which there is uncertainty is whether tension (or the amount of slack) on the mainline during setting affects the sink rate of baited hooks in the shallow depths of the water column. Varying the tension on the mainline alters the underwater shape of the mainline and depths targeted, and is a key component of fishing strategy (Suzuki *et al.*, 1977; Mizunio *et al.*, 1998). Mainline may be set straight off the reel or with a line shooter. A line shooter is a hydraulically

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operated machine through which the mainline is run to achieve the desired level of tension. Setting mainline from the reel involves running the reel at a speed slightly faster than the vessel forward speed such that the mainline enters the water with a slight downward dip 25–40 m astern (exact distance depends on gear, vessel characteristics and wave height). This means that the clip (opposite end of the branch line to the hook) is suspended above the water until the water entry point, which may slow the sinking of the baited hook. Mainline set with a line shooter may be set relatively tightly, as if set from the reel, or it may be set with varying degrees of slackness resulting in additional mainline between floats. Slack in the mainline is achieved by running the line shooter faster than vessel forward speed. Variation in mainline tension may have implications for the sink rates of baited hooks and therefore the period of time sinking hooks are exposed to seabirds.

This paper describes the results of an experiment in Australia's eastern tuna and billfish fishery (ETBF) to determine the effect of mainline tension on the sink rates of baited hooks in surface waters. Surface waters were considered to be the 0–5 m range, where baited hooks are close to the surface and most accessible to seabirds. Vessels in the ETBF generally deploy lines in one of three configurations: surface setting with a tight mainline; surface setting with a loose mainline; or deep setting with a very loose mainline (Figure 1). Vessels surface setting deploy a relatively tight mainline when targeting yellow-fin tuna (*Thunnus albacares*), dolphin fish (*Coryphaena equiselis*) and broadbill swordfish (*Xiphias gladius*), and a loose mainline when targeting yellow-fin tuna and big-eye tuna (*T. obesus*) at greater depths. Deep setting with a very loose mainline is used to target albacore tuna (*T. alalunga*) and big-eye tuna. Actual fishing depths depend on the number of branch lines between floats and hook position in the catena. Time–depth recorder estimates reveal that surface set hooks on tight gear fishes from 25–60 m, surface set loose from 30–80 m, and deep set gear from 60–300 m (source: Australian Fisheries Management Authority). Sink rates of baited hooks attached to mainline under all three tensions were compared in the experiment.

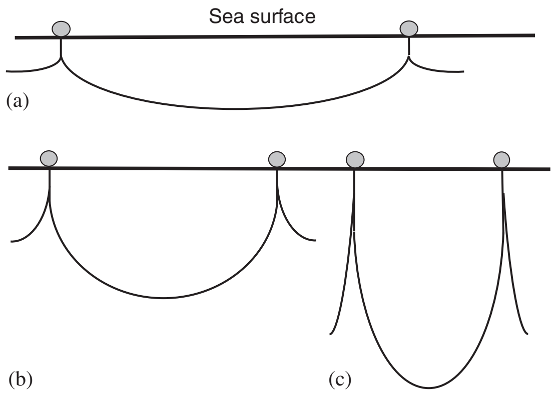

Figure 1. Stylized version of mainline configurations at fishing depth: (a) surface set tight; (b) surface set loose; and (c) deep set loose mainlines.

METHODS

Fishing vessel, location and gear

The experiment was conducted on the F/V *Ocean Explorer* 35 nm east of Mooloolaba (26.41′ S; 153.07′ E), Queensland, Australia, on 2 and 5 May 2008. The *Explorer* is a 22 m long fibreglass 'Westcoaster' vessel rigged to catch tuna and swordfish and was chartered for the experiment (not fishing commercially). In terms of vessel features that may affect the sink rate of the mainline, the *Explorer* set the mainline over the centre line of a single, four blade, 1.25 m diameter, fixed pitch propeller running at 1111 rpm. The mainline was made of 3.5 mm diameter monofilament nylon and was suspended in the water by floats on 10–15 m long downlines. All branch lines were purpose built for the experiment from new materials. Branch lines were 1.8 mm diameter monofilament nylon, 17 m long and measured 14 m from the clip to a leaded swivel and 3 m from swivel to hook. Branch lines were weighted with 60 g leaded swivels, which are required by regulation in the fishery, and baits were attached to 14/0 circle hooks. Nine branch lines were deployed in each float set (see below) and branch lines were deployed every 10 s (36 m apart). Floats were 360 m apart. Thawed pilchards (*Sardinus pilchardus*) hooked through the eye were used as bait. The pilchards ($n = 20$) averaged 80.0 ± 9.6 g in weight and 19.6 ± 0.75 cm in length. The line shooter was mounted at the centre stern of the vessel and the mainline left the shooter 2.4 m above sea level. Setting speed varied from 7–7.3 knots. Wave height was < 1 m on both days and there was no wind. The lines were set across the current (2 knots) on both days of the experiment.

Experimental design

The three mainline tensions examined were (a) shallow set tight mainline ('tight'), (b) shallow set loose mainline ('loose') and (c) deep set loose mainline ('loose plus'). Three replicates of a 3×3 latin square design were used with replicate 1 conducted on day 1 and replicates 2 and 3 on day 2. Each latin square involved three set and haul cycles and within a cycle the order of the three mainline tensions deployed (i.e. block 1, 2, and 3 in that order) was randomized (Table 1, Figure 2). Overall this gave a total of nine sets at the treatment level for the experiment.

Table 1. Treatment order (randomized) within replicates (Rep) for the latin square design of the mainline tension experiment. Treatments were surface setting 'tight', surface setting 'loose' with 2 s of slack, and deep setting 'loose plus' with 7 s of slack. Each treatment comprised three float sets with two TDRs/float set (see text and Figure 2)

Block #	Rep 1			Rep 2			Rep 3		
	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9
1	Tight	Loose plus	Loose	Tight	Loose	Loose plus	Loose plus	Loose	Tight
2	Loose	Tight	Loose plus	Loose plus	Tight	Loose	Tight	Loose plus	Loose
3	Loose plus	Loose	Tight	Loose	Loose plus	Tight	Loose	Tight	Loose plus

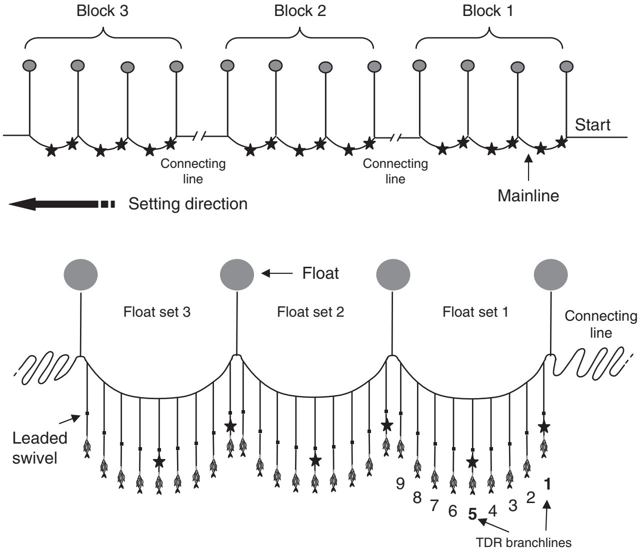

Figure 2. Gear configuration and position of time–depth recorder (TDR) branch lines used in the experiment. As indicated, each treatment of mainline tension comprised three float sets and each float set comprised two TDR positions.

Mainline tension

The line shooter was used for all three mainline configurations. The tight mainline tension was set with the line shooter paying out mainline at the same rate as the forward speed of the vessel ($3.6\,\mathrm{m\,s^{-1}}$). The mainline entered the water about 40 m astern with a slight downward bow, which is usual for this type of setting in calm conditions. The shallow set loose mainline was set with 2 s of slack astern. The degree of slack was determined by holding the mainline by hand and counting the number of seconds before the mainline pulled tight. The deep set loose mainline was set using the same procedure, but with 7 s of slack astern. The amount of slack in both loose tensions resulted in the mainline falling in the water in loose coils about 1 m behind the vessel. The relationship between the vessel forward speed and line shooter speed for each tension was maintained throughout the experiment.

Sampling design and sink rates

Figure 3. Branch line showing 60 g leaded swivel, bait, hook type and position in bait, mainline clip and location of time–depth recorders used in the experiment.

Each set of a mainline tension comprised a series of float sets as shown in Figure 2. Sets commenced by deploying a radio beacon and a large (0.5 m diameter) float to 'anchor' the start of the line. Two float sets of blank mainline (no branch lines) were then deployed to ensure there was enough gear in the water so the start of the line would not drag toward the vessel (important when the first treatment in the setting order was a tight mainline). The first mainline tension, comprising three float sets, was then deployed. At the end of the first tension three non-experimental float sets were paid out to separate the treatments. These three float sets comprised two float sets of mainline set with the same tension as that just deployed to ensure sink rates were not affected by deployment of the next tension (once again, this was especially important when a tight line followed one of the loose lines in the setting order). A third non-experimental float set was then deployed. This third float set was used to provide time for the mainline to be engaged according to the next tension in the set. This process of three experimental float sets followed by three non-experimental float sets was repeated until all three mainline tensions in each set had been deployed.

The sink rates of baited hooks were determined using DC Centi time-depth recorders (TDRs, Star-Oddi Company, Iceland) calibrated to record at 0.07 m intervals every second through a recording range of 1–280 m. The recorders weighed 19 g in air, measured 15 mm × 46 mm and were considered not to have affected the sink rates of baited hooks (Appendix A). The TDRs were attached to branch lines with electrical tape, cable ties and crimps at a distance of 0.20 m from the hooks on 18 branch lines (Figure 3). The exact time of water entry of each TDR was recorded on a digital watch synchronized (nearest second) via the computer with the TDR internal clocks. A total of six TDR branch lines was deployed for each tension within a set, for a total of 18 TDR branch lines for the three tensions per set. Of the nine branch lines per float set, TDR branch lines were attached at positions 1 (closest to the float downline) and 5 (middle of the catena) to examine differences in sink rates related to position in float sets. Since there were nine sets of each mainline tension and each of the 27 sets of three float sets contained two TDR branch lines, a total of 162 ($27 \times 3 \times 2$) TDR branch lines were set for the experiment. On retrieval the TDRs were downloaded to computer, the water entry time (from the digital watch) noted in the time–depth files and the files 'corrected' according the offset at 2 m depth determined in prior tests under controlled conditions for each TDR. The value 10 s after reaching 2 m depth was taken as the calibration offset value because by then the depth readings had stabilized and 10 s is roughly the time taken for baited hooks to pass through the 2 m mark when deployed from a fishing vessel.

TDR branch lines and non-TDR branch lines were deployed on the port and starboard side of the vessel, respectively. TDR branch lines were deployed by holding the baited hook and clip in one hand and the swivel in the other, and using a double-handed action to release both baited hook and swivel (but not the clip). The clip was then attached to the mainline without creating tension in the branch line. Baited hooks on TDR branch lines landed in the water $\geqslant 3$ m past the vessels port side (5–6 m from the centre line of the vessel), about 1 m astern and about 1 m beyond the wake of the vessel (i.e. in non-turbulent water). Thus 5–6 m of the slack in the 17 m long branch lines was taken up in the throw.

Analysis

Sink profiles were analysed as depths to elapsed times, from water entry to 20 s in 1 s intervals using the methods described in Robertson *et al.* (2008). The first 20 s includes the period when hooks are near the surface and considered most accessible to seabirds. Mainline tension was the fixed effect of main interest. However, the effect of branch line position (Figure 2), float set number (Figure 2) and block (1, 2, and 3, Figure 2) were also included as fixed effects to determine if the order of treatments within a set, or the order of float sets within these treatment sets, affected sink rates. All combinations of mainline tension, branch line position, and float set number contained at least two profiles. The zero depth:zero time data points were excluded from the analysis because they have zero variance.

The repeated observations of depth (i.e. depth to time profiles) were modelled using linear mixed models (LMM) (Diggle *et al.*, 2001) 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 and the latter to fit cubic splines to the means. In the non-parametric form of the LMM, 'time' was included as a factor with 20 levels (i.e. times 1–20 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 spline 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 the profile as a sequence of related values, rather than simply a set of means as with the non-parametric LMM. The non-parametric LMM validates the parametric LMM to determine if the combined linear and cubic spline terms adequately modelled the trend in the predicted means obtained from the non-parametric LMM. The random terms in both forms of the LMMs (apart from spline terms in the parametric LMM) were set number (with nine levels, Table 1) and the profile number (with 127 levels, see below).

To account for increasing variance of depth with time given the treatment combination, data were log transformed so that the response variable fitted by the LMM was $y = \log(\text{Depth}+1)$ and predictions on this scale, $\hat{y}$, could be back-transformed to give a predicted depth of $\exp(\hat{y}) - 1$. The autocorrelations 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.

Sink rates in the initial 20 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 zero to 1 m depth which is equivalent to the cumulative sink rate to 1m). Since <1 m depth lay outside the TDR recording range sink rates to this depth were predicted from the LMM using the known time of water entry for each TDR.

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 (see Appendix 2). 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 combinations 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.

RESULTS

Of the potential 162 depth–time profiles 118 were retained for analysis. Of the 44 rejected profiles, 35 were rejected because of spurious TDR readings or improper branch line deployment. A further nine profiles were rejected because they corresponded to the first float set of the tight mainline tension. Profiles from the first float set of the tight mainline tension were rejected because sink rates slowed unexpectedly at about 4 m depth, indicating there was insufficient gear already deployed to prevent subtle dragging of the first float towards the vessel. This is explained further below. In keeping with the main depths of interest in the study, data for all mainline tensions were assessed to 5 m depth, which corresponded to about 20 s elapsed time for the slowest sinking mainline tension.

Table 2. Results of the analysis of variance using sequential Wald statistics for the non-parametric LMM testing for differences in mainline tension (MT), branch line position (BLP) and float set number (FSN). Data for the first float set of the tight mainline has been excluded from the analysis (see text)

Source of variation	D.f.	Sum of squares	Wald statistic (chi square)	*P*
Intercept	1	51.1	817	<0.001
Time	19	427.8	6830	<0.001
Time × MT	40	23.5	374	<0.001
Time × BLP	20	2.2	35	0.019
Time × FSN	40	7.0	112	<0.001
Time × MT × BLP	40	1.5	24	0.980
Time × MT × FSN	80	3.0	48	0.861
Time × BLP × FSN	40	3.7	59	0.027
Time × MT × BLP × FSN	60	3.4	55	0.661

Table 3. Sink times and rates of baited hooks in the 0–5 m (0–20 s) range for the three mainline tensions tested

Depth (m)		Mainline tensions	Mean sink time (s)	Mean sink rate (m s^{-1} ±s.e.)	
Nominal	Predicted[1]			Cumulative[2]	Incremental[3]
1	1.004	Loose	4.2	0.239 (0.012)	0.239
1	1.005	Loose plus	4.2	0.239 (0.012)	0.239
1	1.016	Tight	3.5	0.317 (0.018)	0.317
2	1.992	Loose	11.0	0.181 (0.009)	0.145
2	2.012	Loose plus	9.9	0.203 (0.010)	0.177
2	2.006	Tight	5.8	0.346 (0.010)	0.381
3	3.013	Loose	14.8	0.204 (0.010)	0.269
3	3.007	Loose plus	13.4	0.224 (0.011)	0.284
3	3.013	Tight	8.1	0.369 (0.021)	0.427
4	4.014	Loose	18.0	0.223 (0.011)	0.313
4	4.016	Loose plus	16.6	0.242 (0.012)	0.315
4	3.996	Tight	10.5	0.381 (0.021)	0.419
5	5.013	Loose	20.7	0.242 (0.012)	0.370
5	4.995	Loose plus	19.3	0.259 (0.013)	0.363
5	5.008	Tight	13.2	0.379 (0.021)	0.375

[1] Closest predicted depth (= actual depth) to nominal depth predicted from parametric LMM. Predictions are averaged across the two levels of branch line position and the three levels of float set number.
[2] Cumulative predicted depth ÷ time. SE calculated as SE of predicted depth ÷ time.
[3] Depth increment ÷ time taken to sink from the previous nominal depth.

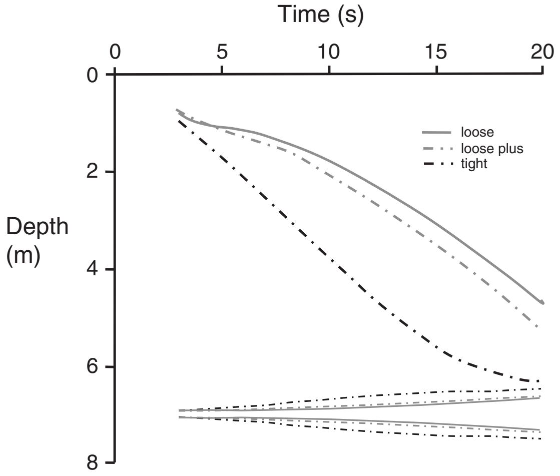

Figure 4. Sink profiles in the 0–5 m depth range (0–20 s) for the three mainline tensions in the experiment. Predictions start from 3 s, or approximately 1 m depth, because the TDRs were not considered sufficiently accurate for shallower depths. The upper and lower 95% confidence bounds for differences between average sink profiles are shown at the bottom of each figure to improve clarity and allow visual comparison of the width of the bounds with the difference between average profiles for each time point (see Appendix B).

Float set number and branch line position

The ANOVA of the non-parametric LMM revealed statistically significant interactions between float set number and branch line position ($P = 0.027$) and the absence of significant interactions between these factors and mainline tension ($P > 0.661$; Table 2). The source of the interaction between float set number and branch line position was the first float set in the loose mainline (Appendix C), where initial sink rates (0–1 m depth) of baited hooks on the fifth branch line exceeded those on the first branch lines. However, sink rates for the first and fifth branch lines in the second and third floats sets on the loose mainline were similar, as were rates for the first and fifth branch lines in all float sets for the other two mainline tensions. Because this difference was confined to only one float set in one mainline tension, and because of the absence of an interaction between branch line position and mainline tension (Table 2), the effect of branch line position on sink rate was considered to be minor. Thus, predictions of depths for given elapsed times for branch line positions were averaged across the float set numbers to simplify the interpretation (see Welham *et al.* (2004) for methods for averaging predictions).

Mainline tension

Overall, the most powerful effect on sink rates was mainline tension (Table 3 and Figure 4). Baited hooks on the tight mainline sank markedly faster than hooks on both loose mainlines, reaching 2 m depth in, on average, 5.8 s (cumulative sink rate: 0.35 m s^{-1}) compared with 9.9 s (0.20 m s^{-1}) and 11.0 s (0.18 m s^{-1}) for the loose plus and loose mainline tensions, respectively. The fastest incremental sink rates for the tight mainline were from 2–3 m depth (0.43 m s^{-1}) and from 3–4 m for the loose (0.37 m s^{-1}) and loose plus (0.36 m s^{-1}) mainlines, respectively. Incremental rates were the same for all three mainline tensions by the time gear had reached 5 m depth.

DISCUSSION

Data treatment

Data from the first float set of the tight mainline tension were rejected because rates slowed at the 4 m mark. This depth (and the time taken to reach it) corresponds to when the slack in the branch lines would have been taken up by the sinking hook, which roughly accords with the time the clip end of the branch line entered the water ~40 m astern of the vessel. Gradual slowing of the sink rates once the slack in the branch lines was taken up indicates there was insufficient gear in the water to prevent slight dragging of branch lines towards the vessel. We were familiar with the effect of dragging, took care to avoid it and saw no evidence gear was being dragged (e.g. floats orientating towards the vessel). There was also evidence of this between 5 and 6 m depth for hooks in the second and third float sets of the tight mainline tension, but not in the 0–5 m depth range. Since the main depths of interest were the 0–5 m range (corresponds to the 0–20 s range) the slight slowing of baited hooks attached to the tight mainlines beyond this range had no bearing on the results and conclusions drawn.

Floats set number and branch line position

The source of the interaction between floats set number and branch line position was the first float set in the loose mainline tension, in which the sink rate to 1 m depth was slower for hooks on the first branch line than the fifth branch line. The float downline was attached to the mainline 36 m from the position of the first branch line and may have added resistance in the propeller turbulence. The difference was not evident for the second and third float sets or for floats sets for the other loose mainline tension, so implicating the position of the float line is not justified. There is no plausible explanation for this finding. In any case, the difference was minor and completely overridden in importance by the primary effect of mainline tension.

Mainline tension

Prior to this experiment it was unclear if a tight mainline could affect the sink rates of baited hooks in the shallow depths. Suspending the clip end of the branch line in the air for 10–12 s astern could either slow the rate at which hooks sank or make no difference at all. Similarly, it was uncertain if paying out varying amounts of loose mainline with the line shooter immediately astern of the vessel would affect sink rates. The results show unequivocally that the tension on the mainline has a strong affect on the sink rates of baited hooks on branch lines attached to it, even when hooks are landed 5–6 m from the mainline. Hooks attached to the two loose mainline tensions sank much slower than those attached to the tight mainline. The greatest difference occurred in the time taken to clear surface waters (e.g. 0–2 m): hooks on tight mainlines sank at more than twice the rate of those on the two loose mainlines. At the 5 m mark incremental rates were similar but tight gear was still about 40% quicker to this depth because of the faster initial rates. The difference most likely can be attributed to propeller turbulence. The two loose mainline tensions were set directly into the turbulence <1 m astern of the vessel whereas the tight mainline was suspended in the air until ~ 40 m astern, at which point it was beyond the area affected by the propeller. Evidently the turbulence held aloft the loose mainlines, slowing the sink rates of the branch lines and baited hooks attached to them.

Implications for seabirds

The findings have implications for the time available to seabirds to attack sinking baits. Assuming baited hooks on the two loose mainline tensions were not drawn into the vessel wake and masked by aerated water from the propeller, with tight gear seabirds would have, on average, just 5.8 s to take baits to 2 m depth compared with 9.9–11 s with loose gear. These differences are substantial, especially for albatrosses, which access baits near the surface. There are also implications for the effectiveness of bird scaring streamer lines, which are recommended worldwide for longline fisheries that interact with seabirds. Setting baited hooks on a tight mainline confers considerable advantage, once again because of the much faster initial sink rates. At 7 knots vessel speed baited hooks on tight mainlines would reach 2 m depth when only 21 m astern ($3.7\,\mathrm{m\,s^{-1}} \times 5.8\,\mathrm{s}$), compared with 40 m and 36 m astern for the loose and loose plus mainline tensions. The comparable estimates for 5 m depth are 48 m astern for the tight mainline and 70–75 m astern for the two loose mainline tensions. For given depths, baited hooks attached to tight mainlines would be much closer to the vessel stern where seabirds can be more easily deterred by effective streamer lines.

Deep setting and seabird interactions

It is assumed by sectors of the ETBF and by some Regional Fisheries Management Organizations (RFMOs; FAO, 2008) that line shooters reduce seabird interactions because they are capable of setting longlines loose and therefore deep in the water column and out of reach of seabirds. This presupposes that seabirds are capable of accessing baited hooks attached to tight mainlines, which are suspended closer to the surface than loose mainlines, during the soak (fishing) period when baits are well beneath the surface, albeit within the diving ranges of some seabird species (e.g. *Puffinus* spp. shearwaters). It also implies that interactions during the soak (if indeed they do occur) might be more significant than during actual line setting operations. Irrespective of method of deployment and amount of tension on the mainline, no objective evidence exists to support the impression that once baited hooks settle at fishing depth they are accessed by seabirds. Even if interactions did occur, the likelihood is they would be much less intense than occurs during line setting. In the absence of convincing evidence to the contrary the prudent interpretation is that seabirds interact with gear during line setting (and hauling) operations when baited hooks are accessible relatively close to the water surface.

CONCLUSIONS AND ADVICE TO MANAGEMENT

Line shooters can be operated to set mainline relatively tight or with varying amounts of looseness. The primary considerations with gear sink rates is not the method of deployment but tension on the mainline and where in relation to propeller turbulence mainline enters the water. These findings indicate that gear set loose with a line shooter into propeller turbulence (as in deep setting) slows hook sink rates in the upper areas of the water column. Assuming a loose mainline does not draw baited hooks into propeller turbulence, where they could be masked by aerated water, loose mainline is likely to increase the exposure of baited hooks to seabirds. Line shooters are used routinely in the ETBF as part of fishing strategy and promoted by some RFMOs to reduce interactions with seabirds. However, unless mainlines can be set to avoid propeller turbulence the use of line shooters for deep setting is likely to increase the risks to seabirds. Since line shooters are typically positioned on vessels to deploy mainline into propeller turbulence, deep setting should not be promoted as an effective deterrent to seabirds.

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APPENDIX A: EFFECT OF DC CENTI TDR ON SINK RATES

Trials were conducted in a 3.0 m high, 2.0 m diameter tank of seawater at the Australian Antarctic Division to determine if the DC Centi TDRs used on the *Ocean Explorer* affected the sink rates of baited hooks. The diameter of monofilament branch line, weight of leaded swivel, bait species, hook size and hooking position in baits were the same as used in the experiment at sea (see Methods). The bait used in the tank was slightly lighter (74.0 g) and shorter (SL: 16.5 cm) than the average of the bait used at sea (see Methods). The same individual bait was used for the tank trials. TDRs were attached to the branch line 0.1 m from the eye of the hook with miniature cable ties. For each trial baits were dropped 15 times with a TDR attached and 15 times without a TDR attached. Sink times were recorded to the nearest 1/100 s with a digital stop watch. Data were standardized as time-to-known depth for analysis. The following three separate trials were conducted:

Initial sink rate with slack line between swivel and hook

At sea, the initial sink rate refers to the elapsed time between the baited hook landing in the water and when the sinking swivel (sinks faster than baited hook) takes up the slack in the section of line between swivel and hook. Prior to this moment the baited hook and swivel free fall, with the latter exerting minimal pull-down on the former. This configuration occurs when the swivel and baited hook are thrown so as to land close to one another, which creates slack in the branch line connecting them. In the tank trial the baited hook and swivel were joined by a 3 m length of monofilament, as in the experiment at sea. The swivel and baited hook were held 1.5 m apart at the water surface with the 1.5 m of slack monofilament (to make up the 3 m) lying loosely in the water. The baited hook was secured with a piece of fine (0.16 mm) monofilament which was payed out without resistance as the hook sank. Both swivel and hook were released simultaneously and the swivel timed to the tank bottom with the stop watch. When the swivel hit the bottom the fine monofilament attached to the hook was gripped, preventing further sinking. The length of nylon from grip point to eye of the hook was measured with a tape measure to provide an estimate of drop depth. Since gripping of the line occurred simultaneously with the moment the swivel hit the tank bottom, the drop depth of the baited hook could be converted to sink rate, which was used in the analysis.

Baited hooks with and without the TDR averaged 0.49 ± 0.03 (s.d.) $\mathrm{m\,s^{-1}}$ and $0.41 \pm 0.02\,\mathrm{m\,s^{-1}}$, respectively. The difference was statistically significant (ANOVA: $F_{1,29} = 77.3$; $P < 0.001$). With this configuration the addition of a TDR increased the initial sink rate of the baited hook by, on average, $0.08\,\mathrm{m\,s^{-1}}$.

Initial sink rate with tight line between swivel and hook

At sea, this configuration simulates the situation where baited hook and swivel are thrown such that they land in the water separated by the length of the monofilament line connecting them. In the tank trial the methods were as for the above except the swivel and hook were separated by 1.5 m of monofilament line which was stretched tight across the width of the tank. Both swivel and baited hook were held at the surface and released simultaneously and swivel timed to the tank bottom. The pull-down of the swivel drew the baited hook towards it such that when the swivel reached the bottom of the tank the baited hook was positioned directly over the swivel. Since the water column was 3 m deep and the swivel and hook separated by 1.5 m, each drop of baited hook was 1.5 m. This depth and the time taken to reach it were used to estimate sink rates.

The average sink rates of baited hook set with and without a TDR attached were $0.44 \pm 0.01\,\mathrm{m\,s^{-1}}$ and $0.44 \pm 0.02\,\mathrm{m\,s^{-1}}$, respectively. With this configuration there was no detectable difference associated with the addition of a TDR to the branch line.

Final sink rate

At sea, final sink rate occurs on completion of the initial phase of sinking when the monofilament between swivel and baited hook is taut and the swivel exerts maximum pull down on the baited hook. Final sink rate occurs a few metres beneath the surface (depends on length of connecting line and relative sink rates of baited hook and swivel). In the tank the swivel was attached with cable ties 0.1 m below the TDR, which was 0.1 m from the eye of the hook. The baited hook was held horizontal to the water surface allowing the swivel and TDR to hang beneath it. The baited hook was released and timed to the bottom of the tank.

The baited hook under load of the sinking swivel set with and without a TDR attached averaged $0.91 \pm 0.02\,\mathrm{m\,s^{-1}}$ and $0.91 \pm 0.02\,\mathrm{m\,s^{-1}}$, respectively. There was no detectable effect of the TDR on the sink rate of the baited hook.

CONCLUSION

The trials in the tank indicate that the addition of a DC Centi TDR to the branch lines used on the *Ocean Explorer* was unlikely to have affected final sink rates. With respect to initial sink rates, the branch lines on the *Ocean Explorer* were thrown such that swivel and baited hook landed in the water separated by about 2.5 m of the 3 m length of line joining them. The sinking swivel would have taken up the ~0.5 m of slack line and engaged the baited hook very quickly. Overall, we conclude that the addition of TDRs to the branch lines on the *Ocean Explorer* was unlikely to have made a discernible difference to the sink rates.

APPENDIX B: 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 six extra variance parameters (i.e. for times 1, 2, 3, 4, 5–9, 10–20 s with corresponding factor denoted TIME.g) to the constant variance form of the LMM. Incorporating an extra variance parameter for every time point above 5 s over-parameterized the model as indicated by the relatively small increase in the residual log-likelihood (excluding constants) from 4294 to 4325. Table B1 shows that the variance for the 5 to 9 s class increased slightly over the 10 to 20 s class while there was a large increase for the 4 s time and moderate increases for each of 1, 2, and 3 s time points. The residual log-likelihood dramatically decreased to 4064 when this trend in variances was not modelled. 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 nine sets. The corresponding estimates for the non-parametric and parametric LMMs fitted to the data excluding the nine profiles mentioned above are not given since they were very similar to the estimates given in Table B1.

Explanation of confidence bounds

Differences between average profiles for a given time that are greater than the 95% confidence bounds shown in the figures (displayed at the bottom of the figures for clarity) 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 (see Methods), the bounds will depend on which set of predicted mean depths have been used. The

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

	Variance	s.e.	Z-ratio
Set	8.995×10^{-3}	6.465×10^{-3}	1.391
P-unit.TIMEg (1,2]	6.227×10^{-3}	1.176×10^{-3}	5.297
P-unit.TIMEg (2,3]	5.657×10^{-3}	1.199×10^{-3}	4.717
P-unit.TIMEg (3,4]	4.158×10^{-3}	0.984×10^{-3}	4.224
P-unit.TIMEg (4,5]	2.336×10^{-3}	0.681×10^{-3}	3.433
P-unit.TIMEg (5,10]	1.471×10^{-3}	0.480×10^{-3}	3.061
P-unit.TIMEg (10,20]	0.0	—	Boundary value
EU residual variance	62.638×10^{-3}	9.068×10^{-3}	6.908
Autocorrelation	0.975	0.004	252.5

bounds for each level of the factor used in the comparison are shown. Visual comparisons between pairs of factor levels should use the average of the bounds relevant to the comparison.

APPENDIX C

Relationship between float set number (FSN) and branch line position (BLP). The interaction between these two factors is shown in the 0–1 m depth range of the loose mainline tension. Predictions start from 3 s, or approximately 1 m depth, because the TDRs were not considered sufficiently accurate for shallower depths. The upper and lower 95% confidence bounds for differences between average sink profiles are shown at the bottom of each figure to improve clarity and allow visual comparison of the width of the bounds with the difference between average profiles for each time point (see Appendix B). See text for explanation why the sink profile for the first float set has been removed from the tight mainline tension.