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New branch line weighting regimes to reduce the risk of seabird mortality in pelagic longline fisheries without affecting fish catch

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ABSTRACT

1. Experiments were conducted on two new branch line weighting regimes designed to reduce the risk of seabird mortality in the Australian pelagic longline fishery. The experiments compared the sink rates and fish catch rates of the new regimes with that used by the fishing industry.

2. Baited hooks on gear with a 120 g lead weight 2 m from the hook reduced the time to reach 2 m, 5 m and 8 m depths by 16%, 58% and 70%, respectively, compared with industry standard gear with 60 g at 3.5 m. Baited hooks with 40 g leads at the hook reduced the time taken to reach 2 m, 5 m and 8 m depth by 33%, 28% and 25%, respectively. The reduction in time with a 60 g lead at the hook to these depths was ~40%.

3. There were no statistically detectable differences in catch rates of target and non-target fish between industry standard branch lines and branch lines with both 120 g leads at 2 m and those with 40 g leads at the hook. The results contest the widely-accepted opinion that major branch line modifications, including weight at the hook, reduce fish catch.

4. The regime with a 40 g lead at or very close to (i.e. ≤ 0.5 m) the hook has the most potential for adoption in fisheries due to: (i) improved crew safety; (ii) ease of port-based inspection for compliance purposes; (iii) reduced construction costs; (iv) reduced bin tangles; and (v) ease of deployment. Lead loss from shark bite-offs can be minimized by placing leads on short (≤ 0.5 m) leaders. In areas of moderate to high risk to seabirds, or where the risks are unknown, the use of 60 g leads either at or ≤ 0.5 m from the hook is encouraged.

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KEY WORDS: pelagic longline fisheries; seabird bycatch; fish catch rates; branch line weighting; hook sink rates; innovation; cooperative research

INTRODUCTION

Pelagic longline fisheries for tunas and tuna-like species are responsible for the deaths of large numbers of albatrosses and petrels throughout the southern hemisphere (Waugh *et al*., 2008; 2010; Jiménez *et al*., 2009; Tuck *et al*., 2011) and are considered a main cause of reduced population sizes at many breeding sites (Robertson and Gales, 1998 and references therein; Poncet *et al*., 2006). In Australia seabird mortality in pelagic longline fisheries mainly occurs in the Eastern Tuna and Billfish Fishery. This fishery operates off eastern Australia with 30–40 fresh (non-freezer) vessels. Effort peaked at 13 million hooks in the early 2000s but since 2007 has ranged from 7–9 million hooks per year (source: Australian Fisheries Management Authority [AFMA]). The main seabird species

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affected are fleshy-footed shearwaters (*Puffinus carniepes*), great-winged petrels (*Pterodroma macroptera*) and *Diomedia* spp. and *Thalassarche* spp. albatrosses (Baker and Wise, 2005; Trebilco *et al*., 2010). Seabird bycatch rates ranged from 1.88 birds per 1000 hooks in 2001 to 0.02 birds per 1000 hooks in 2006 (Trebilco *et al*., 2010). Seabird conservation is managed under a Threat Abatement Plan, which stipulates mortality rates must not exceed 0.05 birds per 1000 hooks in any 5° latitudinal band in any 6 month season of the year (AAD, 2006). To meet this standard fishers are required by legislation to adopt seabird bycatch mitigation measures as part of fishing permit conditions under the Australian Fisheries Management Act (1992). Requirements vary depending on geographic region and bycatch history (AAD, 2006) but in general include combinations of weighted branch lines, bird scaring streamer lines, offal retention during line setting and the night-setting of longlines. In the winter (April–September) season of 2008 the seabird bycatch rate was breached by five observed vessels off south-eastern Australia, prompting a day-setting prohibition in that sector of the fishery. These captures indicated that the mandated line weighting in combination with a single streamer line (with dead and live bait and day-setting) could not prevent the seabird bycatch rate from being exceeded under all conditions and that further research was required to reduce the likelihood of the bycatch limit being breached in the future.

When used in combination the four mitigation measures mentioned above are highly effective in reducing seabird mortality (ACAP, 2011). However, for reasons related to operational flexibility and fishing efficiency, industry operators prefer to set lines at the timing of their choice to optimize catch, rather than be restricted to night-setting only. In the Australian fishery bird scaring streamer lines often fall short of the specifications in permit conditions, especially the aerial extents, which are the key component of deterrence. These typically range from 40–50 m, far less than the 90 m required in fishing permits (source: AFMA). There are also unresolved issues with entanglements in fishing gear (Domingo *et al*., 2011) which are an impediment to adoption, non-compliance and monitoring thereof (Azócar *et al*., 2011), which requires either high levels of on-board observer coverage, electronic monitoring or aerial surveillance, all of which are costly. The problem of increased seabird bycatch associated with non-compliance is minimized (or avoided, depending on the fishery) with line weighting. Once lead weights are fitted in branch lines they become an intrinsic part of the fishing gear. On the short (up to ~15 days) trips typical in Australia and in many other coastal state fisheries it is neither practical nor cost effective to remove them. Furthermore, in coastal state (not on the high seas) fisheries branch lines are typically stored in bins (Figure 1) which facilitates port-based inspection to monitor compliance. For these reasons branch line weighting was chosen as the focus of further research to reduce seabird mortality in the Australian pelagic longline fishery.

This paper reports the results of experiments involving two new branch line weighting regimes. Both regimes are considered to be new because one involved much greater weight on a much shorter leader (distance between weight and hook) than traditionally used by the industry, and the other involved a weight placed at the hook. Hitherto weight at the hook has been strongly resisted by industry owing to concerns about effects on fish catch. Both experiments involved comparison with the industry-standard line weighting, which is a 60 g lead weight (typically a leaded swivel) crimped into branch lines ≤ 3.5 m from hooks. Both new regimes were designed to sink baited hooks much faster than hooks on industry-standard branch lines and thereby reduce the availability of baits, and risks, to seabirds. The first regime involved branch lines with a 120 g lead weight ≤ 2 m from hooks. This regime was recommended by Robertson *et al.* (2010a) following research on the key determinants of hook sink rates in both the upper and lower reaches of the water column. The second experiment compared industry standard line weighting with branch lines equipped with a 40 g lead weight placed at the hook. This was a new type of lead custom-made for the project. Both 120 g and 40 g leads were the sliding type designed to improve crew safety (see below and Sullivan *et al*., 2012). Because a collaborator could not be found in a high risk area of the fishery both experiments were conducted in an area with relatively low seabird abundance. Thus the focus was on the effects of the new fast-sinking weighting regimes on the catch rates of target and non-target fish species. This was an attempt to address the commonly (and strongly) held opinion by fishers that weight at the hook or on very short leaders reduces fish catch. If no (or very minor) effects were revealed an important

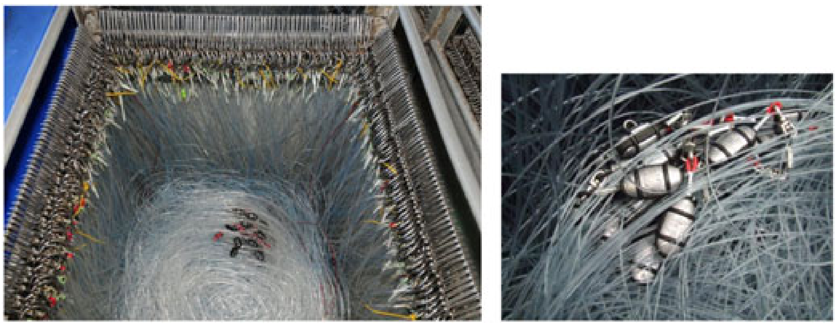

Figure 1. Branch line bin of the F/V *Samurai* as used in the 120 g experiment (left). Clips (one end of the branch line) are attached to horizontal wires around the top of the bin and hooks (at the other end of branch lines) are suspended from the clips. The bulk of the branch lines is coiled in the bin along with the line weights. The weights in the photo on the left are 60 g safe leads. The 120 g safe leads used in the 120 g experiment are shown on the right.

impediment to the adoption of fast sinking gear will have been removed. Benefits to seabird conservation are based on the assumption that fast-sinking gear reduces the availability of baits to seabirds and thus the likelihood of incidental capture and death.

METHODS

Understanding hook sink profiles

The following summary from Robertson *et al.* (2010a) provides information fundamental to experiments designed to improve gear sink rates. The sink profile of baited tuna hooks varies depending on the mass of the added weight and length of the leader. Hooks on branch lines with long leaders typically sink in two distinct stages – slow initially then faster. The initial sink rate is slow because the weight does not fully engage with the hook until the leader becomes taut, which may be several seconds after deployment (depends, principally, on leader length but also drag from the bait). Until that point the effect of the weight is minimal. For a given weight the longer the leader the slower the initial sink rate. Baited hooks that sink slowly initially are more likely to be attacked by seabirds than those that sink quickly from the surface. Once the leader is taut the sink rate depends on the mass of the added weight. The fastest initial sink rates are achieved by placing weight at – or very close to (e.g. 0.5 m) – the hook.

Fishing vessel and gear

General

Both experiments were conducted on the F/V *Samurai*, which is a 20-m fibreglass semi-planning hull 'Westcoaster'. The F/V *Samurai* operates out of Mooloolaba (26.68°S; 153.1°W) in south-eastern Queensland, Australia. The F/V *Samurai* set a 3.2 mm monofilament mainline through a line shooter in the surface set loose configuration (Robertson *et al.*, 2010b). The mainline was suspended on floats on a mix of 10 m and 20 m long droppers. Branch lines were made of 1.8 mm monofilament nylon, 16 m long and were fitted with #14/0 circle hooks. Baited hooks were deployed to the outer edge of vessel wake on both sides of the vessel. The bait was a mix of whole squid (*Illex argentines*) and pilchard (*Sardinus pilchardus*). All baits were dead. Branch lines with squid bait were always accompanied by a light stick placed 2 m from hooks. Light sticks were never used with pilchard bait. A typical set on the F/V *Samurai* involved deploying 1200–1450 hooks at 8 knots vessel speed with 10 branch lines between floats and branch lines 35 m apart. Branch lines were set from gear bins every 8 s off both sides of the vessel. Radio beacons were deployed at 200 branch line intervals. The main species targeted in the experiments were yellow-fin tuna (*Thunnus albacores*), big-eye tuna (*T. obesus*) and broad-bill swordfish (*Xiphias gladius*). Time-of-day of line setting varied with moon phase and operational issues, but in general commenced at nautical dusk when targeting swordfish and early morning when targeting tunas.

120 g at 2 m versus 60 g at 3.5 m experiment

In this experiment, hereafter call the 120 g experiment, sleeves and skirts (considered to attract fish) were distributed randomly throughout gear and some branch lines were not equipped with either. Sleeves are 10 cm × 0.5 cm tubes of fluorescent rubber latex fitted tightly over branch lines immediately above the hooks. Skirts are placed in the same position and comprise a rosette of multi-coloured rubber latex strands that resemble squid tentacles and dangle over the top section of the hook. At the start of the experiment the proportion of the 600 branch lines with 120 g lead weights at 2 m fitted with sleeves, skirts or nothing was 38%, 21% and 41%, respectively. The equivalent figures with 60 g at 3.5 m were 54%, 21% and 25%. By the third set of the first trip the gear had been re-configured so that the proportions were equal for both gear types. Those proportions were maintained for the remainder of the experiment. Bait species – squid alone, pilchard alone or an even mixture of both – and setting depth were kept constant within pairs but occasionally changed between pairs. Light sticks, which are used to attract swordfish, were attached 2 m from hooks to branch lines with squid bait. The 120 g leads were safe leads (Sullivan *et al.*, 2012) which are designed to avoid recoiling if a branch lines breaks, is bitten off under tension or the hook pulls from the fishes mouth during hauling, which is hazardous to crews. They were twice the weight of standard safe leads and were custom-made for the experiment (Figure 1).

40 g hook lead versus 60 g at 3.5 m experiment

This experiment, hereafter called the 40 g hook lead experiment, involved the development of a new type of lead weight (see *Acknowledgments* for the origin and manufacturer of this lead type). This lead is threaded onto (not crimped into) branch lines to enable it to slide and was designed to be located at – or very close to (e.g. 0.5 m) – the hook. Both 40 g and 60 g versions were available for the experiment. Both leads have the same dimensions except that the end of the 40 g version is recessed to fit over the crimp above the hook whereas the 60 g version is square-ended and abuts the crimp. The leads are cylindrical in shape, have a cap on one end that is hand tightened until it grips the monofilament, and are designed to slide in the same manner as safe leads if the branch line breaks under high load. They are coated with 2 mm luminescent nylon and glow in the dark (Figure 2). The 40 g version was chosen for the experiment following comparison of the sink profiles of various weighting regimes in static water (Appendix A). The choice of the 40 g over the 60 g version was based on the markedly improved sink rate of the former compared with industry standard gear and the fact that the experiment was conducted in an area of the fishery of relatively low risk to seabirds.

The fishing gear and specifications, bait species and the number of branch lines deployed in sets were the same as for the 120 g experiment. Skirts and sleeves were fitted to 60 g gear, not to branch lines with 40 g hook leads. At the start of the experiment the proportions of 1200 branch lines fitted with skirts, sleeves or nothing (plain ended) were 7%, 38% and 55%, respectively. Skirts were progressively removed from gear during routine line maintenance and by the start of the fourth trip (of 10 trips in total) the proportions had reduced to <1%, 3.5% and 95.5%, respectively. On sets with light sticks, blue, green, pink and white light sticks were deployed in equal numbers.

Experimental design

120 g experiment

This experiment was conducted over six fishing trips and 30 sets of the longline between March and

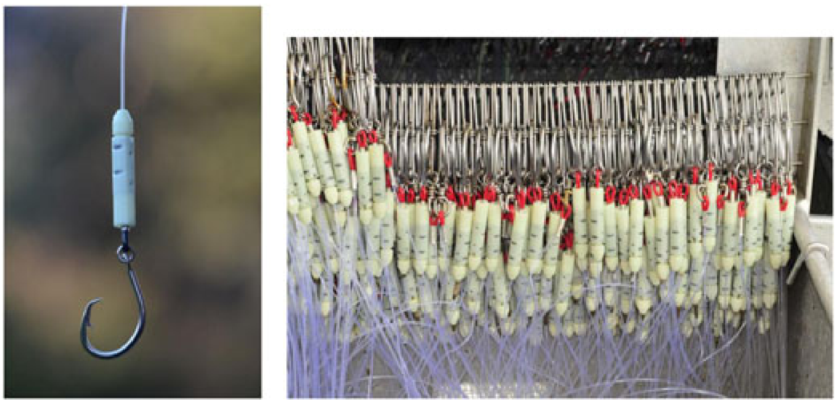

Figure 2. A 40 g hook lead and # 14/0 circle hook showing the luminescent nylon coating on the lead and its position in relation to the hook (left). To improve crew safety the lead is threaded onto (not crimped into) the branch line, is hand tightened (via the screw cap at the top) onto the monofilament and slides if the line breaks under tension (see text). The lower one-third of the lead is recessed to fit over the crimp. The photo on the right shows the position of the hook leads (and their visibility in terms of port-based inspection for compliance monitoring) when stored in the gear bins.

December 2010. The experiment involved setting gear in pairs with each pair comprising 200 branch lines with 60 g weights at 3.5 m from the hook and 200 branch lines with 120 g at 2 m from the hook. Each group of 200 branch lines was flanked by a radio beacon. Either two or three pairs (800–1200 branch lines in total) were deployed in each set of the longline. The order in which weighting regimes were set was alternated between sets to avoid systematic bias associated with setting order. Depth of setting varied with fishing strategy but was constant for each group of 200 branch lines comprising a pair. The variable recorded during line hauling was the number by taxa of all fish caught. The experiment yielded a combined total of 31 200 hooks set and 78 pairs for analysis. These comprised 12 pairs with pilchard bait only, 45 pairs with squid only and 21 pairs with mixed baits.

40 g hook lead experiment

This experiment ran from February to November 2011, involved 10 fishing trips, 50 sets of the longline and yielded 70 594 hooks available for analysis. The design of this experiment followed that for the 120 g experiment except that instead of alternating between groups of 200 branch lines of each weighting regime the two regimes (60 g at 3.5 m and 40 g at the hook) were alternated with each consecutive branch line deployed. With respect to bait, 44 of the 50 sets were single bait sets and six were mixed bait sets (three other mixed bait sets were excluded because the relative proportion of bait species used was not recorded). Of the single bait sets 29 deployed only squid baits and 15 deployed only pilchard baits. The majority of branch lines deployed were baited with squid (44 582 hooks) and the remainder (26 012) with pilchards (squid to pilchard ratio: 1.77:1).

Estimating hook sink rates

The sink rates of baited hooks with 40 g at the hook and 60 g at 3.5 m were estimated from the F/V *Samurai* on 21 November under charter conditions (all extraneous factors controlled). The sink rates of gear with 60 g at the hook and 60 g at 1 m from the hook were also assessed. The first regime was included in case faster sink rates were required in the future in seabird-rich areas of the fishery, and the second was tested as a potential option to minimize lead loss in areas where the incidence of shark bite-offs is excessive. Ten branch lines of each weight configuration were purpose built from new materials. Branch lines were 14.5 m long and fitted with # 14/0 circle hooks (15 g) and dead pilchard hooked through the eye. Three radio beacons were deployed at the start of the longline to prevent dragging (Robertson *et al.*, 2010b). Floats on 7 m dropper lines were deployed every eight hooks (following every second group of the four different weighting regimes). Vessel setting speed averaged 6.8 knots. The mainline was set through a line shooter in the surface set tight configuration (Robertson *et al.*, 2010b) and entered the water 25–30 m astern beyond the main area affected by propeller turbulence. Baited hooks were deployed to land 2–3 m outside the wake zone on the starboard side of the vessel. Branch lines were deployed in groups of four – one branch line of each of the four regimes – throughout each set to avoid bias associated with setting order. Each branch line was deployed three times in three sets of the longline (30 replicates per weight regime). Sink rates were estimated with Cefas G5 time-depth recorders (2.25 g in water, 3 cm resolution) attached to branch lines < 10 cm from the hook and programmed to record time and depth every second.

We were unable to determine the sink rate of branch lines with 120 g at 2 m along with the other regimes at sea on the F/V *Samurai*. Instead, the sink rate was estimated in static water along with the four regimes above which were included for comparative purposes (Appendix A).

Gear loss and line repairs

Leads at the hook are more vulnerable to loss from being bitten off by sharks (and possibly fish with small teeth) than leads located away from the hook. The number of leads of each type that were bitten off was recorded in 23 hauls over five fishing trips (trips 6–10). The number of branch lines of each weighting regime that required maintenance was also recorded. The reasons branch lines of both weighting regimes required repair were hook loss (from bite-offs), chaffing of the monofilament near the hook (occurs when sharks rub against the line under tension) and kinks caused by the incorrect attachment of light sticks.

Statistical methods

In both experiments counts of fish by species and species groups were obtained for each weight regime by set within trip combination. In the 120 g experiment the tabulations were pairs with sets and weight regime within pair. Bait species was allocated at the set level. Bait species groups were pilchard only, squid only and a mix of both. In the 40 g experiment tabulations were carried out for combinations of weight regime by bait species within sets. The bait categories were pilchard or squid allocated for each branch line that captured a fish (see below). In addition to the count data constructed for the 40 g hook lead experiment, a second data set was constructed for squid baits only to examine the possible interaction between light stick colour (but not presence or absence) and line weighting regime. The fish counts were tabulated by weight regime and light stick colour from 29 sets in seven trips where squid baits were used exclusively.

The fish counts from both experiments were analysed as a Poisson generalized linear mixed model (GLMM) with log link (Robertson *et al.*, 2006) using the R-software (R Development Core Team, 2008) and the ASREML-R library (Gilmour *et al.*, 1999). This approach uses penalized quasi-likelihood for the estimation (Candy, 2004).

The response variable analysed in both experiments was the number of fish caught in each set. In the case of swordfish in the 40 g hook lead experiment, the GLMM analysis of bait species x weight regime failed to converge because all but one fish were caught on one bait type (squid). To overcome this problem a linear mixed model was fitted to the log of the count data after adding 1 (this model converged). In the 120 g experiment each pair of 200 branch lines was uniquely identified as the random effect factor. The comparison of mean catch rates between weight regimes and bait species combinations were expressed as the number caught per 1200 hooks. This hook number was the number of hooks in three pairs, which were the commonest number of pairs in each set in the experiment. In the 40 g hook lead experiment (weight regimes alternated by branch lines), for the sake of consistency with the 120 g experiment, the count of fish caught was also expressed as a catch rate per 1200 hooks, along with the combination of bait species if mixed baits were used in sets. The unique set-within-trip identifier, where set was equivalent to a pair for the 120 g experiment, was used as the random effect factor. Fishing trip number was also included as a random effect but it was consistently estimated to contribute a non-significant ($P > 0.1$) amount to the total variation. In both experiments depth of setting was excluded from the analyses. In the 120 g experiment depth was kept constant within pairs and in the 40 g hook lead experiment depth was varied between sets but not within sets. Unlike bait species there is no reason to envisage a reason for an interaction between line weighting regime and setting depth.

In comparisons of mean rates for statistical significance the standard error of the difference (SED) between means was approximated by the average standard error of the difference on the log-link scale, obtained from *ASREML-R* function *predict*, multiplied by the mean rate. Note that including random effects results in predicted mean catch rates being smaller than means based on the raw data (random effects ignored). In addition, this may affect the bait species comparison considered as a main effect since in the majority of sets a single bait species was deployed. Since set within trip was included in the GLMM as a random effect, high catch rates for particular sets will be down-weighted because of large positive random effect estimates for these sets.

Mixed bait sets with unknown proportions were a substantial proportion of total sets in the 120 g experiment but not in the 40 g experiment (they were removed in the latter experiment, as mentioned above). This required that bait species be treated differently between the two experiments. In the 120 g experiment bait was pilchard only (5 sets), squid only (17 sets) and a mix of both (8 sets). The proportion of these two species deployed within these sets was not accurately recorded. The number of hooks deployed was 200 per combination of trip, set, pair and line weight regime, so it was not necessary to explicitly account for effort. This is only the case if bait species was specified with the extra category of mixed baits at the set level and not at the branch line level. For the six retained mixed bait sets in the 40 g experiment the number of hooks deployed for each bait species was known so the variable hooking effort by weight regime and bait species combination could be accounted for. Therefore bait species has only two categories of pilchard and squid in the 40 g trial and hooking effort, which varied in the range 300–920 per set, was accounted for by using the log of number of hooks as an offset in the Poisson GLMM (Candy, 2004).

The statistical method for analysing time-to-depth profiles and corresponding sink rates followed Robertson *et al.* (2010a, b). The results of the light stick analysis are presented in Appendix B.

RESULTS

Fish catch effects: 120 g experiment

Yellow-fin tuna

In total, 626 yellow-fin tuna were caught (both weighting regimes and all bait groups combined). The interaction between weight regime and bait species was not significant but the effect of bait species was statistically significant (Table 1). Irrespective of weighting regime, gear with pilchard baits caught more yellow-fin tuna than gear with squid bait or a mix of squid and pilchards. This result was, however, strongly influenced by one of the six fishing trips when a large number of yellow-fin tuna were caught with pilchard baits by both weighting regimes. Importantly, there was no significant effect of weighting regime on the catch rates of yellow-fin tuna (Table 1). Differences between gear types in mean catch rates on sets employing only pilchard baits were not statistically significant ($P > 0.1$), with mean catch rates of 63.1 fish per 1200 hooks and 66.08 fish per 1200 hooks by 60 g and 120 g gear, respectively (SED = 21.03). The same was true for sets with only squid baits, with mean catch rates of 4.5 fish per 1200 hooks on 60 g gear and 3.7 fish per 1200 hooks on 120 g gear (SED = 0.69). Mean catches for sets with a mix of pilchards and squid were estimated but are not interpretable because the exact proportions of the two bait species deployed across all hooks in a set were not known.

Other commercial species

Other commercial species caught were big-eye tuna, albacore tuna (*T. alalunga*), blue fin tuna (*T. maccoyi)*, broad-bill swordfish, dolphin fish (*Coryphaena hippurus*), and short-finned mako (*Isurus oxyrinchus)* and long-finned mako (*I. paucus*) sharks. The numbers caught (418) of these species were too low to be treated separately so the data for each were pooled. There was no significant effect of bait species (pilchards, squid and a mix of pilchards and squid), nor was there an effect of weighting regime (Table 1). Within bait group the mean catch rates per 1200 hooks were similar. The mean catch rate on 60 g gear and pilchard bait was 12.82 fish per 1200 hooks compared with 14.87 fish per 1200 hooks on 120 g gear (SED = 5.19). Mean catch rates with sets with only squid baits were 20.03 fish per 1200 hooks on 60 g gear and 16.42 fish per 1200 hooks on 120 g gear (SED = 3.05).

Fish catch effects: 40 g hook lead experiment

Yellow-fin tuna

In total, 970 yellow-fin tuna were caught during the experiment (both bait species combined). Of these 397 yellow-fin tuna were caught on squid baits and 573 on pilchard bait. There was no significant interaction between bait species and weighting regime, nor was there a statistical difference in catch rates of yellow-fin tuna between bait species or between the two weighting regimes (Table 2). Mean catch rates for both bait species were 10.65 fish per 1200 hooks with the 40 g hook leads and 10.39 fish per 1200 hooks with 60 g at 3.5 m gear (SED = 0.62). Mean catch rates for squid baits were 10.99 tuna per 1200 hooks with the 40 g hook leads and 10.72 fish per 1200 hooks with 60 g at 3.5 m gear (SED = 0.64).

Big-eye tuna

In total, 77 big-eye tuna were caught on squid and pilchard bait groups combined. Of these 75 big-eye tuna were caught on squid baits. There was a significant effect of bait species with pilchards giving a lower catch rate. However there was no significant interaction with weighting regime (Table 2). Therefore the catch rates of big-eye tuna were averaged over both bait species: 40 g gear averaged 0.21 fish per 1200 hooks compared to 0.24 fish per 1200 hooks on 60 g gear (SED = 0.03 across both bait species). Mean catch rates for squid baits were 0.89 fish per 1200 hooks with the 40 g hook leads

Table 1. Results of analyses of variance for the 120 g experiment testing for the effect of branch line weighting regime (60 g at 3.5 m versus 120 g at 2 m) and bait species on the numbers of yellow-fin tuna and six other commercial species combined (see text).

Fish spp.	Source of variation	Df	SS	Wald statistic	Probability (chi squared)
Yellow-fin tuna	Bait species	2	23.79	37.34	<0.0001
	Weight regime	1	0.23	0.36	0.55
	Bait spp. x weight regime	2	0.11	0.17	0.92
	Residual (Mean Square)		0.64		
Other commercial species	Bait species	2	8.9	4.71	0.095
	Weight regime	1	2.14	1.13	0.29
	Bait spp. x weight regime	2	1.35	0.71	0.67
	Residual (mean square)		1.89		

Table 2. Results of an analysis of variance for the 40 g hook lead experiment testing for the effect of bait species and branch line weighting regime (60 g at 3.5 m versus 40 g at the hook) on the numbers of fish caught of each species/species group (see text).

Fish spp.	Source of variation	Df	SS	Wald statistic	Probability (chi squared)
Yellow-fin tuna	Bait species	1	0.13	0.16	0.69
	Weight regime	1	0.15	0.18	0.67
	Bait spp. × weight regime	1	1.10	1.32	0.25
	Residual (mean square)		0.84		
Big-eye tuna	Bait species	1	2.78	7.27	0.007
	Weight regime	1	0.32	0.85	0.36
	Bait spp. × weight regime	1	0.01	0.02	0.88
	Residual (mean square)		0.38		
Albacore tuna	Bait species	1	0.29	0.64	0.42
	Weight regime	1	1.38	2.97	0.08
	Bait spp. × weight regime	1	1.92	4.13	0.04
	Residual (mean square)		0.47		
Broad-bill swordfish	Bait species	1	8.13	23.91	<0.001
	Weight regime	1	0.66	1.94	0.16
	Bait spp. × weight regime	1	0.86	2.52	0.11
	Residual (mean square)		0.34		
Dolphin fish	Bait species	1	0.11	0.13	0.71
	Weight regime	1	0.04	0.05	0.82
	Bait spp. × weight regime	1	0.27	0.32	0.57
	Residual (mean square)		0.85		
Sharks	Bait species	1	1.17	1.38	0.24
	Weight regime	1	1.61	1.91	0.17
	Bait spp. × weight regime	1	0.01	0.01	0.93
	Residual (mean square)		0.84		

and 1.01 fish per 1200 hooks with 60 g at 3.5 m gear (SED = 0.13). These differences are not statistically significant (Table 2).

Albacore tuna

In total, 404 albacore tuna were caught on all bait groups combined; 340 of these were caught on squid baits. There was a significant interaction ($P = 0.04$) between bait species and weighting regime (Table 2). However, the interaction effect reduces to a single parameter estimate for the combination of the 60 g weight and pilchard bait of 0.38 (SED = 0.278) with a t-test indicating a P-value greater than 0.05. Sequential Wald tests can be ‘anti-conservative’ in the case of mixed models (Welham and Thompson, 1997) so it is prudent to only reject the null hypothesis based on Wald tests with P-values less than 0.01. Therefore the catch rates of albacore tuna can be averaged over both bait species types: 40 g gear averaged 1.04 fish per 1200 hooks compared with 1.17 fish per 1200 hooks on 60 g gear (SED = 0.08 across both bait species types). Mean catch rates for squid baits were 1.37 fish per 1200 hooks with the 40 g hook leads and 1.54 fish per 1200 hooks with 60 g at 3.5 m gear (SED = 0.10).

Broad-bill swordfish

In total, 218 swordfish were caught on all bait groups combined. Virtually all (217) were caught on squid baits. The GLMM analysis of bait species × weight regime failed to converge (because of all but one fish being caught on pilchard bait) so a linear mixed model was fitted to the log of the count data after adding 1 (this model converged). There was no significant interaction between bait species and weighting regime (Table 2). Mean catch rates for squid baits were 3.21 fish per 1200 hooks with the 40 g hook leads and 3.74 fish per 1200 hooks with 60 g at 3.5 m gear (SED = 0.39). These differences are not statistically significant (Table 2).

Dolphin fish

In total, 203 dolphin fish were caught on all bait groups combined. Squid bait accounted for 151 of the number caught. There was no significant interaction with weighting regime, and there was no statistical difference in catch rates of dolphin fish between bait species or between the two weighting regimes (Table 2). Mean catch rates over both bait species were 1.94 fish per 1200 hooks with the 40 g hook leads and 1.88 fish per 1200 hooks with 60 g at 3.5 m gear (SED = 0.25). Mean catch rates for squid baits were 1.83 fish per 1200 hooks with the 40 g hook leads and 1.78 fish per 1200 hooks with 60 g at 3.5 m gear (SED = 0.23). These differences are not statistically significant (Table 2).

Shark species combined

The shark species considered were dusky (*Carcharhinus obscures*), silky (*C. falciformis*), smooth hammer head (*Sphyrna zygaena*), blue (*Prionace glauca*), short-finned mako and long-finned mako sharks. In total, 158 sharks were caught on all bait groups combined. Of these 114 sharks were caught on squid baits. There was no significant interaction with weighting regime, and there was no statistical difference in catch rates between bait species or between the two weighting regimes (Table 2). Mean catch rates over both bait species were 1.94 sharks per 1200 hooks with the 40 g hook leads and 2.38 sharks per 1200 hooks with 60 g at 3.5 m gear (SED = 0.32). Mean catch rates for squid baits were 2.26 sharks per 1200 hooks with the 40 g hook leads and 2.77 sharks per 1200 hooks with 60 g at 3.5 m gear (SED = 0.37). These differences are not statistically significant (Table 2).

Sink times and rates

In the static water test baited hooks attached to standard gear (60 g at 3.5 m) sank much slower than the other four regimes throughout the entire depth range (8 m). Baited hooks on 120 g at 2 m reached 2 m, 5 m and 8 m depths in 16%, 58% and 70% less time, respectively, than the times taken by hooks on standard gear. In terms of elapsed time, baited hooks on 120 g at 2 m branch lines reached 8 m depth in less than 10 s compared with ~17 s taken by standard gear. The times taken for hooks attached to branch lines with 120 g at 2 m, 40 g at the hook, 60 g at the hook and 60 g at 1 m to reach 2 m and 5 m deep were statistically indistinguishable (Appendix A). At 8 m depth the first three regimes were statistically similar but the 60 g at 1 m regime was significantly slower than 120 g at 2 m, which was the fastest to this depth (Appendix A). On average, the fastest regime (120 g at 2 m) reached 8 m depth in 15% less time than the slowest (60 g at 1 m).

The sink profiles on the F/V *Samurai* followed the order expected from the static water trial. Branch lines with 60 g at the hook sank the fastest followed by 40 g at the hook, 60 g 1 m from the hook and 60 g 3.5 m from the hook (Figure 3). The differences between all four profiles were statistically significant throughout the entire depth range.

The average times taken for the four regimes to reach various depths in the water column and associated average sink rates are shown in Table 3. The results are presented to 8 m depth only because thereafter they were held up by the mainline, nullifying the relevance of further comparison. Gear with 40 g hook leads averaged

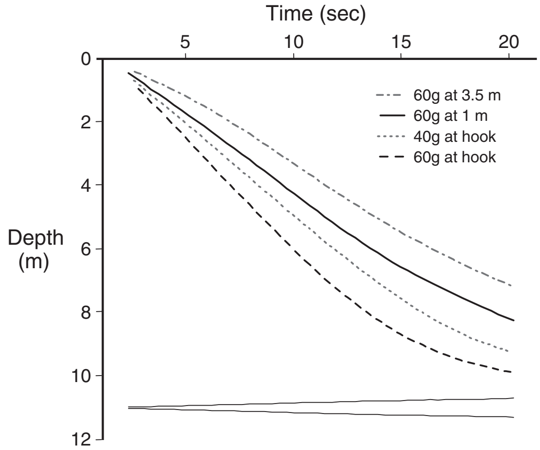

Figure 3. Mean sink profiles of the line weighting regimes (60 g at 3.5 m and 40 g lead at the hook) compared in the fish catch experiment. Profiles for the 60 g lead at the hook and 60 g at 1 m are also shown because they have potential relevance to the fishery (see Appendix A1 for the profile for the 120 g at 2 m regime). The 95% confidence bounds are shown as horizontal bars at the bottom of the figure. If the difference between any two average profiles for a given time exceeds the difference between the upper and lower arms of the confidence bounds then the difference is statistically significant. N = 30 replicates for each regime.

Table 3. Mean sink times and sink rates to target depths of the two branch line weighting regimes in the 40 g hook lead fish catch trial. Also included are results for 60 g hook leads and 60 g leads 1 m from hooks (see text). N = 30 replicates per weight regime.

Line weight regime	Nominal depth (m)	Time to depth (s)	Sink rate ($m s^{-1}$)
40 g at hook	2	4.52	0.43
60 g at hook	2	3.96	0.51
60 g at 1 m	2	5.22	0.39
60 g at 3.5 m	2	6.76	0.29
40 g at hook	5	9.70	0.51
60 g at hook	5	8.16	0.61
60 g at 1 m	5	11.10	0.44
60 g at 3.5 m	5	13.58	0.37
40 g at hook	8	15.58	0.51
60 g at hook	8	13.06	0.61
60 g at 1 m	8	18.94	0.42
60 g at 3.5 m	8	20.90	0.39

4.5 s to 2 m deep (0.43 $m s^{-1}$) compared with 6.7 s (0.29 $m s^{-1}$) for 60 g at 3.5 m. The results to 5 m were 9.7 s (0.51 $m s^{-1}$) and 13.6 s (0.37 $m s^{-1}$) for the 40 g hook lead and 60 g at 3.5 m, respectively.

Gear loss and line repairs

In total, 33 050 branch lines (in 23 sets) were monitored for lead loss and branch line repair. Half (16 525) of these branch lines were weighted with 60 g at 3.5 m from the hooks and the other half with 40 g hook leads. The number of branch lines that required repair was 964 and 858 for the 60 g gear and 40 g gear, respectively. Of these, leads were lost from 24 branch lines of the former regime and 179 branch lines from the latter regime. All losses of leads from both gear types also involved loss of the hooks. These figures equate to an average of 1.5 and 10.8 leads per 1000 hooks for the 60 g and 40 g hook leads, respectively. The average mass of lead lost was 0.0087 kg per 1000 hooks of 60 g leads and 0.43 kg per 1000 hooks of 40 g hook leads.

The numbers of branch lines that required repair for reasons other than lost leads and hooks (line chaffing, line kinks) were 940 of 60 g gear (e.g. 964–24, see above) and 679 of 40 g gear (858–179) for the 23 sets monitored. Thus an average of 16 fewer branch lines per 1000 hooks of 40 g hook lead gear required repair than 60 g gear (e.g. 679 ÷ 16 525 c.f. 940 ÷ 16 525).

DISCUSSION

120 g experiment

Fish catch effects

There was no detectable difference between line weighting regimes in the catch rates of yellow-fin tuna and seven other commercially valuable species. This finding is important because it demonstrates that major modifications to branch lines – in this case use of a lead weight and leader twice the mass and nearly half the length, respectively, as those on conventional branch lines – can be made without affecting the number of fish landed.

Sink rates

In the static water trial baited hooks on 120 g at 2 m gear reached 5 m and 8 m depths in 58% and 70% less time, respectively, than on industry standard gear. The time saving (16%) in the 0–2 m range was less than to the other depths (and less than gear with 40 g hook leads; see below) because of the 2 m leader, which causes a lag at the surface (Robertson *et al.*, 2010a). The results demonstrate the benefits to both initial and final sink rates of shortening the leaders and increasing the mass of the line weights.

Operational considerations

The main operational consideration with the 120 g leads is the extra weight in the gear bins. These leads add 30 kg to the weight of a standard 500 branch line bin. This makes the bins more difficult to move between setting and hauling positions on vessels. The leads would also increase the cost of the fishing gear. Ultimately, however, these issues must be weighed against the benefits to seabird conservation which include, potentially, the freedom to fish without the threat of prohibition on the day-setting of longlines or closure of fishing grounds in seasons of high abundance of longline-vulnerable seabirds.

40 g hook lead experiment

Skirts and sleeves

The effect, if any, of skirts and sleeves on fish catch rates in the early part of the experiment is unknown. However, the number of skirts used was very minor, as was the number of branch lines with sleeves on the last seven of the 10 trips in the study (see Results). It is unlikely the number of sleeves on 60 g gear on the first three trips affected the overall comparison of the two line weighting regimes.

Fish catch effects

Fish catch rates were highly variable and some species were caught very infrequently. The sample sizes are statistically adequate only for the commonest species caught (it would be time and cost prohibitive to gather statistically viable sample sizes for all species of fish caught in the fishery). Fish taxa or groups of taxa for which there were adequate data for analysis include yellow-fin tuna, big-eye tuna, albacore tuna, broad-billed swordfish, dolphin fish and five species of sharks combined. There were no statistically discernible differences in the catch rates of the abovementioned species/groups between branch lines with 40 g hook leads and those with 60 g leads at 3.5 m. Mean catch rates of yellow-fin tuna, big eye tuna, albacore tuna and dolphin fish were virtually identical among the two gear types.

With respect to sharks, hook leads shield the lower 8 cm of the branch line, which includes the area that may be bitten, and weakened, by sharks. Protection of the monofilament near the hook may increase the incidence of shark bycatch. Only sharks that were still attached to branch lines in the final stages of hauling, not those that had bitten themselves free (see lead loss, below), were included in the analysis. Of the sharks that remained attached to the line in the final stages of hauling there were no differences in catch rates between industry standard branch lines and those with 40 g lead weights at the hook. As with the 120 g experiment, the results for the 40 g hook lead experiment indicate that weight can be placed at the hook without affecting fish catch rates.

Sink times/rates

The results of the sink times/rates from the F/V *Samurai* are more informative than those in the static water trial because they reflect the influence of vessel movement, propeller turbulence and sea state. Gear with 40 g leads at the hook reduced the surface time (0–2 m) from 6.7 s to 4.5 s, a 33% reduction in time available to seabirds to access baits compared with hooks on industry standard branch lines. The saving to 5 m depth was nearly 4 s, equating to 28% less time. The time saved near the surface is explained by the instantaneous sinking (no lag due to the absence of a leader) of the baits with leads at the hook. Although the 60 g leaded swivels were 20 g heavier, the loss of time at the surface due to the 3.5 m long leader was not recovered deeper in the water column (Figure 2). This is also demonstrated by the result for the 60 g at 1 m regime. A 1 m leader is short, yet this regime was outperformed by that with 40 g at the hook (this was also evident in the static water trial (Appendix A)). In another study (Robertson *et al.*, 2010a) baited hooks on branch lines configured with 160 g lead weights (four-times the mass of the 40 g hook leads) 2 m from the hook were 37% and 11% slower to 2 m and 5 m depths, respectively, than the 40 g hook lead gear in the current study. These results highlight the advantage of placing lead weights either at the hook or on very short (i.e. 0.5 m) leaders. They further indicate that increasing the mass of existing weight located some distance from the hook (e.g. 2 m) is far less beneficial than reducing the length of the leaders.

Comparison of sink times/rates with some previous studies is difficult to justify due to the potentially confounding effect of TDR mass (e.g. 60 g in air in Brothers *et al.*, 2001 versus 5.7 g in this study) on sink rates, uncertainty over some aspects of sampling methodology (Brothers *et al.*, 2001) or sampling methods not comparable with those in the current study (Anderson and MCardle, 2002: use of 5 m long leaders compared with ≤ 1 m in this study; sink times/rates in the critical initial phases of sink profiles not assessed). The sink rates of baited hooks with 40 g (0.43 m s^{-1} to 2 m; 0.5 m s^{-1} to 5 m) and 60 g (0.51 m s^{-1} to 2 m; 0.61 m s^{-1} to 5 m) leads at the hook are the fastest we know of for gear with line weights of similar masses set from pelagic longline fishing vessels.

Potential benefits to seabirds

Assessment of risk reduction is based on the reasonable (and logical) assumption that superior sink rates reduce the availability of baits to seabirds. The most relevant expression of sink rates is in terms of the aerial sections of bird scaring lines, which are effective in deterring albatrosses and petrels (Brothers, 1991; Melvin *et al.*, 2010; Domingo *et al.*, 2011), and seabird dive depths. Ideally gear should reach maximum seabird dive depths (or be as deep as possible) when ≤ 50 m astern, which is the typical length of the aerial sections of scaring lines of Australian vessels (see above). Estimates of depth versus distance astern for various weighting regimes are shown in Table 4, which is compiled from the sink rate estimates in Table 3 and based on a setting speed of 8 knots (4.1 m s^{-1}) over the water. Of the three regimes shown the most important comparison is industry standard weighting with the 60 g hook lead gear because the latter regime is encouraged for areas considered medium to high risk to seabirds (see below). At 5 m depth, which approximates the maximum dive depth (4.5 m) of black-browed albatrosses (*T. melanophrys*; Prince *et al.*, 1994), gear with industry standard weighting would be 6 m beyond the protection zone of scaring lines whereas gear with 40 g and 60 g hook leads would be 10 m and 17 m, respectively, within the protected area. At 8 m depth, which approximates the maximum dive depth (7.4 m) of shy albatrosses (*T. cauta*; Hedd *et al.*, 1996) baited hooks on industry standard gear would be 36 m past the end of the aerial section compared with 14 m and 4 m past this area for 40 g and 60 g hook lead gear, respectively. White-chinned petrels (*Procellaria aequinoctialis*), which can reach 13 m depth (Huin, 1994), would be able to access baited hooks past the aerial sections but would need to expend greater effort to access hook lead gear which would be deeper in the water column than

Table 4. Estimated distances astern to target depths as a function of vessel setting speed and the sink rates of various line weighting regimes. The sink rates of the weighting regimes shown are drawn from Table 3. Estimates are for a setting speed of 8 knots (4.1 m s^{-1}) over the water.

Depth (m)	Distance astern (m)		
	60 g at 3.5 m	40 g at hook	60 g at hook
2	27.8	18.6	16.3
5	55.8	39.9	33.5
8	85.9	64.0	53.7

industry standard gear owing to the superior sink rates. Finally, in the event scaring lines are routinely not used, as reported in the Chilean swordfish fishery (Azócar *et al.*, 2011), and longlines are set at times of fisher choice, including during daylight, line weighting would be the only safeguard against elevated levels of mortality. With this in mind the prudent option is the adoption of weighting regimes that sink gear as fast as is practically possible.

Gear loss and line repairs

The only drawback with the 40 g hook leads was the number of leads and hooks lost. Leads and hooks were lost at seven times the rate of the 60 g leaded swivels, owing to bite-offs, presumably by sharks. Losses occurred unevenly throughout the experiment and in areas of high shark activity. The 60 g gear was bitten off just as regularly but the lead weights were not lost as frequently (24 versus 179 weights for the hook leads) because the leads and hooks were 3.5 m apart. Blue sharks, which are abundant in the fishery, are presumed to be the principal cause for the bite-offs. The main concern is not the economic loss (see below) but the number of lead weights lost to the sea bed or swallowed by sharks. Ingested lead may affect the health of sharks and be deposited in the meat, which in some parts of the world is used for human consumption. The frequency of lead loss should be monitored in the future. The option for replacing lead with another material (such as occurs in some recreational fishing) could also be investigated.

The solution to excessive lead loss is to place leads on very short leaders. The choice of leader length depends not only on the typical bite-off length but the height of the hook suspension rails on gear bins (Figures 1 and 2). The latter is important so that all leads will be visible in gear bins (not hidden beneath the coils of monofilament) when inspected in port for compliance purposes. Observations in an area of high blue shark abundance in the south Atlantic Ocean indicate that placing leads 0.5 m from hooks will minimize losses from bite-offs (G. Robertson, personal observations). Gear bins should be configured so the suspension rails are high enough to accommodate leaders of this length.

The average loss rate of leads and hooks per 1000 branch lines reported above (1.5 and 10.8 for 60 g and 40 g gear, respectively) equates to US$2.70 for 60 g gear and $16.95 for 40 g gear. These estimates are based on the current unit cost of 60 g leaded swivels (US$1.00), the estimated US$0.75 per lead for commercially available 40 gm hook leads and the current unit cost of US$0.82 for the #14/0 circle hooks used in the experiment. The extra cost is offset to some degree by reduced labour and materials in construction (see below) and by lower overall repair requirements, which averaged 16 branch lines per 1000 lines fewer than 60 g gear. Unfortunately we did not quantify the exact reasons why each line type required repair. However, the main reasons were line chaffing and line kinks, in addition to loss of leads and hooks. While the loss of hook leads always resulted in the loss of the hooks (from bite-offs), with 60 g gear on 3.5 m leaders sharks often took the hooks but not the weights, because of the 3.5 m distance between the two. Assuming half of the extra 16 per 1000 branch lines of 60 g gear were repaired due to lost hooks, the cost difference would reduce to ~ US$7.70 (8 lines × US$0.82 per hook + $2.70 for the lost leads). When considered against the costs of other aspects of fishing operations (fuel, bait, lights sticks, vessel and gear maintenance) this extra cost is minor. Locating leads ≤ 0.5 m from hooks should remove any financial difference between the two gear types in relation to bite-offs.

Crew safety and compliance monitoring

In addition to improved sink rates and reduced likelihood of seabird captures, the other important considerations with the hook leads (and line weighting in general) are crew safety and monitoring compliance with the line weighting requirements of fishing permits. With respect to the former, the incidence of dangerous fly backs from bite-offs or line breaks is greatly reduced with leads that slide located at or close to the hook. When under load the leads either remain at the hook or slide up the branch line, sometimes as far as the clip. In the former case a bite-off involves both lead and hook, thereby eliminating the chance of dangerous fly back. In the latter case only the hook will be bitten off. In that event the behaviour of the lead depends on its position in the branch line. If close to the bitten off area it is likely to fly off the open ended branch line. If a few metres from the end of the branch line it is likely to slide as the branch line recoils, dissipating much of the force. If it has slid several metres away or as far as the clip there will be minimal or no recoil force. In all cases, as far as line breaks and bite-offs are concerned leads located at or near the hook with the capacity to slide are a much safer option than leaded swivels crimped into branch lines.

The other safety concern is when hooks pull from the fishes mouth. If hooks on gear with industry standard line weighting pull from the mouth they recoil in the same manner as bite-offs, except both the leaded swivel and hook are propelled towards the vessel, albeit as two objects 3.5 m apart. If leads are placed at the hook, pull-outs could potentially result in both hook and lead flying back as one object. However, this rarely happens. Owing to their location in the branch line the hook and lead are either underwater or at the water surface when the hook pulls from the mouth. The water acts to dampen the force of recoil. In addition, hook pull-outs are far less common than line breaks and bite-offs. Of the 34 935 branch lines set with hook leads in the experiment (half of the total number set) pull-outs occurred only three times and only once did the hook travel as far as the vessel. Since the experiment ended 79 000 branch lines with hook leads have been set and only two pull-outs recorded (N. Williams, personal records). One recoiled to within 1 m or so of the vessel and the other struck a crewman without causing injury. The latter occurred at the sea door when the fish was about to be landed on deck. Contact could have been avoided had better care been taken (N. Williams, personal communication). Thus it is concluded that leads at or near the hook with the capacity to slide on the branch line under load improve crew safety compared with conventional leaded swivels crimped into branch lines. Finally, the nylon coating on the leads prevents contact with lead, which is a toxic metal, when handling gear.

With respect to compliance monitoring, port-based assessments of industry standard line weighting are problematic because the leaded swivels lie scattered among several kilometres of monofilament line in gear bins (Figure 1). Gear bins may hold several hundred branch lines and it is not practical to remove them for inspection. This problem is avoided with branch lines configured with leads at the hook or on very short leaders because the leads are suspended from suspension rails well clear of the monofilament and easily observed (Figure 2).

Other considerations

A number of operational advantages became evident during the experiment. These were noted by one of us (SH) who completed seven of the 10 trips in the experiment.

1. Reduced labour: branch lines with the industry standard weighting comprise two lengths of monofilament line crimped to either side of a leaded swivel. The leader must be measured and cut to the length required by permit conditions. Branch lines with hook leads consist of a single straight-through section of monofilament joining clip (snap) and hook. The swivel at the clip is sufficient to prevent the line from twisting. Gear with hook leads can be constructed in about half the time of that with leaded swivels crimped into the lines.
2. Reduced tangles: mixing leaded swivels with monofilament in gear bins increases the incidence of line tangles during deployment. Tangles slow setting operations and increase the necessity for repair/replacement. Bin tangles rarely occur with leads at the hook because the leads are stored free of the coils of monofilament (Figure 2). This would also be the case with leads on very short leaders.
3. Reduced line breakage: the crimps holding leaded swivels in place are made of aluminium. When lead and aluminium make contact in gear storage bins in the presence of water the crimps corrode and split, potentially resulting in line breakage and lost fish. The nylon coating on the hook leads prevents metal-on-metal contact and eliminates the incidence of line breakage due to crimp failure.
4. Reduced seabird capture at hauling: when hauled with an automatic line hauler, industry standard branch lines must be removed from the hauler at the leaded swivel. This leaves the hook, sometimes with intact bait, dangling in the water beside the vessel, providing an opportunity for seabirds to attack baits and become hooked. Branch lines with leads at or very close to the hook remove this opportunity because branch lines can be hauled until hooks are at the hauler and beyond the reach of seabirds.
5. Ease of deployment: industry standard gear requires crew to bait the hook, pay out a section of branch line before attaching a light stick and then pay out enough line so the leaded swivel drags in the water behind the vessel. This procedure is necessary to reduce line tangles. With branch lines with leads at the hook the step of dragging the hook in the water is eliminated. The hook, bait and lead are handled and thrown as one.
6. Reduced cost: hook leads are cheaper to produce than conventional leaded swivels. The cost saving must be weighed against the cost of replacing leads bitten off by sharks. As mentioned, the loss

of leads can be minimized by placing them on very short leaders.

The final point relevant to the above is the potential for self regulation. Maintenance of leads in their correct positions on branch lines – either at the hook or very close to the hook (in waters where bite-offs are excessive) – depends on the diligence and consistency of crews. The advantages listed above provide strong incentives for crews to maintain the leads in the required position.

CONCLUSIONS

By virtue of their far superior sink rates compared with industry standard gear the two weighting regimes tested are a significant advance in terms of reducing potential risks to seabirds. Just as importantly, the results challenge the accepted (but hitherto untested) opinion that heavy weights on relatively short leaders, and weights at the hook, reduce fish catch. This is clearly not the case. The findings from both experiments remove an impediment to the adoption of line weighting regimes with potential to reduce the risk of seabird bycatch in pelagic longline fisheries.

Implementation in fishery

Based on the improved sink profiles, absence of effects on fish catch and improved crew safety, in January 2012 the permit conditions of fishing operators in Australia's pelagic longline fishery were modified to allow the option of 40 g lead weight at the hook in addition to the current regime of 60 g at $\leq$ 3.5 m from the hook. The modification applies only to operators fishing wholly with dead bait (not a mix of dead and live bait).

MANAGEMENT ADVICE

The evidence suggests that compared with the standard line weighting, regimes with a 120 g lead weight at 2 m and a 40 g lead weight at the hook do not affect the catch rates of target and non-target fish. The latter regime has substantial advantages pertaining to improved sink rates, improved crew safety, ease of compliance monitoring, cost reduction and ease of operation. Management organizations are encouraged to consider adoption of hook leads in their fisheries. In areas where lead loss from bite-offs is considered excessive 40 g leads should be placed on $\leq$ 0.5 m leaders. In areas of unknown or moderate to high risk to seabirds the use of the heavier 60 g leads within 0.5 m of the hook is encouraged. The suspension rails in gear bins should be of sufficient height for all leads to be suspended above the coils of monofilament and visible on port inspection. For safety reasons the leads should be the sliding type threaded onto, not crimped into, branch lines.

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Both experiments were conducted with Mr Nick Williams, owner/operator of the F/V *Samurai*. Mr Williams and his crew tolerated the operational imposts associated with the 120 g trial (heavier bins, repeated bin changes during setting as required by the experimental design) and accepted the risk of potential reduction in fish catch rates with the new weighting regimes. They are to be commended for their efforts.

The idea of a sliding lead placed at the hook came from Mr Williams and one of us (SH). These leads are an extension of the original safe lead concept developed by Fishtek Pty Ltd., UK (www.fishtek.com; see Sullivan *et al*., 2012) in that they are designed to slide on branch lines to dissipate energy in the event of breakage under tension (safe leads were used in the 120 g experiment reported above). The sliding lead concept and the idea to place leads at the hook were significant breakthroughs in terms of improved crew safety and faster sink rates. Mr Williams, SH and Fishtek jointly designed the sliding hook leads used in the experiment. The leads were manufactured and supplied by Fishtek Pty Ltd.

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APPENDIX A

Static water trial

The sink profiles and sink rates and times to target depths of various branch line weighting regimes were investigated from a moored vessel in the sea near Hobart, Australia. The weighting regimes examined were 120 g 2 m from the hook and the four regimes tested at sea on the F/V *Samurai* (60 g lead weight at the hook; 60 g weight 1 m from the hook; 60 g lead weight 3.5 m from the hook; 40 g lead weight at the hook). The same branch line (20 m long), hook type and bait species were used in all comparisons. Each regime was deployed 30 times by hand so the hook landed 5–7 m outboard of the vessel (as with the F/V *Samurai*). Sink rates were estimated with a single G5 TDR attached at the hook and the results analysed as for the F/V *Samurai*. The results are shown in Figure A1 and Table A1. The sink time to 2 m depth of the 60 g/1 m regime was identical to that of the 120 g/1 m, indicating the benefit of short leaders. The sink profiles and time taken to reach target depths of all experimental regimes were far superior to the industry standard regime. The regime with 40 g at the hook was preferred for the experiment on the F/V *Samurai* on the grounds of superior performance compared with the industry standard regime and because the region of the fishery where the F/V *Samurai* (and other vessels) operated was an area of relatively low abundance of longline vulnerable seabirds.

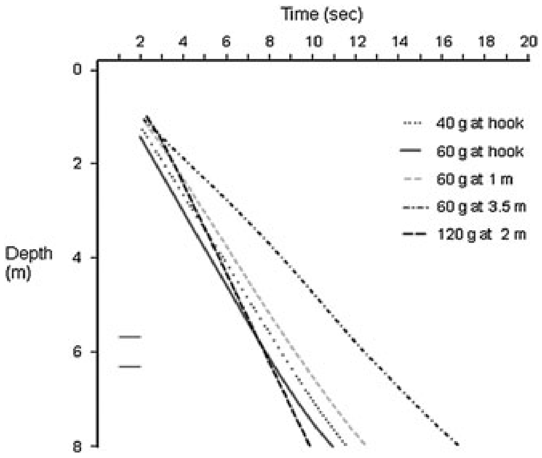

Figure A1. Mean (n = 30) sink profiles of the 60 g at 3.5 m, 120 g at 2 m and 40 g at the hook line weighting regimes. The 95% confidence bounds are shown as two short horizontal bars near the y-axis of the figure. If the difference between any two average profiles for a given time exceeds the difference between the upper and lower arms of the confidence bounds then the difference is statistically significant.

Table A1. Static water comparison of mean (n = 30) sink times and sink rates of baited hooks set on industry standard branch line weighting regime (60 g at 3.5 m) with the 120 g at 2 m, 40 g at the hook, 60 g at the hook and 60 g at 1 m weighting regimes

Line weight regime	Nominal depth (m)	Time to depth (s)	Sink rate ($m\,s^{-1}$)
40 g at hook	2	3.08	0.65
60 g at hook	2	2.63	0.77
60 g at 1 m	2	3.53	0.56
60 g at 3.5 m	2	4.16	0.48
120 g at 2 m	2	3.53	0.56
40 g at hook	5	7.22	0.69
60 g at hook	5	6.68	0.75
60 g at 1 m	5	7.76	0.65
60 g at 3.5 m	5	10.64	0.47
120 g at 2 m	5	6.78	0.75
40 g at hook	8	11.54	0.69
60 g at hook	8	11.0	0.73
60 g at 1 m	8	12.26	0.65
60 g at 3.5 m	8	16.67	0.48
120 g at 2 m	8	9.83	0.82

APPENDIX B

Effect of light sticks: 40 g hook lead experiment

The line weighting regime of interest is that with 40 g hook leads because branch lines with these leads and light sticks contained two objects that glowed, which may have affected fish catch. Of the line sets with squid bait, 5825 hooks were set with each of the four light stick colours. There was no statistical interaction between light stick colour and weight regime for the catch rates of yellow-fin tuna ($P = 0.57$). Similarly, there was no interaction regards the catch rates of albacore tuna ($P = 0.36$). There was a significant interaction of light stick colour on dolphin fish catches but this effect was weak ($P = 0.04$) and the sample size too small to justify definitive conclusions. The main finding relates to broad-billed swordfish, which is the main species for which light sticks are deployed. There was a significant interaction between light stick colour and weighting regime in the number of this species caught (Table B1 and B2). Industry standard branch lines with white light sticks caught three times more swordfish than branch lines with 40 g hook leads and white light sticks. There was no difference in catch rates related to the other three light stick colours. This result suggests that swordfish are deterred from 40 g hook lead gear by the presence of a white light stick located 2 m above the hook. Note, however, that the sample size was only 229 swordfish among two weighting regimes and four light stick colours. A much larger sample size is required to confirm the accuracy of this finding. In the meantime it would be prudent to avoid the use of white light sticks on 40 g hook lead gear when targeting swordfish.

Table B1. Results of an analysis of variance testing for the effect of branch line weighting regime and light stick colour on the catch rates of broad-bill swordfish

Source of variation	Df	SS	Wald statistic	Probability (chi squared)
Light stick colour (LSC)	3	11.448	13.395	0.004
Weight regime (WR)	1	3.268	3.824	0.051
LSC x WR	3	10.583	12.383	0.006
Residual		0.855		

Table B2. Predicted mean catch rates per 1200 hooks by weight regime and light stick colour for broad-billed swordfish

Weight regime	Light stick colour	Mean catch rate per 1200 hooks[a]
40 g at hook	Blue	3.730
40 g at hook	Green	3.464
40 g at hook	Pink	2.531
40 g at hook	White	2.131
60 g at 3.5 m	Blue	3.996
60 g at 3.5 m	Green	3.730
60 g at 3.5 m	Pink	1.998
60 g at 3.5 m	White	6.128

[a] SED = 0.943