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Two devices for mitigating odontocete bycatch and depredation at the hook in tropical pelagic longline fisheries

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Odontocete bycatch on and depredation from tropical pelagic longlines is globally widespread, having negative impacts on the economic viability of affected fisheries and on the conservation of affected odontocete populations. Reports by fishers that depredating odontocetes avoid gear tangles has underpinned the development of simulated structures to physically deter depredating odontocetes. This study assessed the efficacy of two such devices developed to mitigate odontocete depredation and associated bycatch. Of particular interest was their impact on (i) soak depth and (ii) sink rate using truncated trials, before determining their impact under full operational conditions on rates of (iii) catch of the five most economically important fish, and (iv) odontocete depredation and bycatch, on changes in (v) fish survival and size, and (vi) setting and hauling speed. The results indicated that the inclusion of devices on longlines had negligible impact on soak depth, thus were unlikely to impact on the suite of fish specifically targeted and caught. The sink rate was slowed, perhaps by drag, trapped air, or propeller wash, although the addition of weight might remedy this if the devices were to be used in areas where seabird bycatch could occur. Most importantly, trials conducted in Australian and in Fijian waters indicated that pooled fish catch rates (i.e. albacore, yellowfin, bigeye, mahi mahi, and wahoo) increased in the presence of the devices, possibly because more fish were attracted by them or because more depredators were deterred. Catch rates on control gear next to gear with devices attached were higher than more distant control gear, suggesting the influences of the devices may have extended to adjacent branchlines. The size of caught fish was mostly unaffected, although the survival of yellowfin and bigeye increased significantly in the presence of the devices. Hauling was slowed by the use of the devices and the need for an extra crewmember during setting and hauling, which could be cost prohibitive in some fisheries, especially if economic benefits from their use are not obvious. Despite the small sample size, odontocete bycatch only occurred on unprotected fishing gear and all individuals were released alive, although their fate was uncertain; there was evidence of injuries sustained from the event. The outcomes are positive and should motivate stakeholders to view such devices as a potentially effective tool for mitigating odontocete bycatch and depredation in this and similar longline fisheries. Future efforts should focus on improving operational integration and reducing implementation costs to encourage voluntary uptake and thus avoid non-compliance and the need for costly monitoring. The use of this technology could bring about marked improvements to the conservation situation for affected odontocete populations and to the economic situation for affected longline fisheries.

Keywords: acoustic, cetacean, conservation, economic, mortality, operational interactions, physical, toothed whale, tuna, viability.

Introduction

As the human population increases globally, so too does the demand for food (Gilland, 2002). Technological advances since World War II underpin the order of magnitude expansion of commercial and industrial fishing effort in coastal and offshore waters, contemporarily placing unprecedented and widespread pressure on most targeted fish populations (Pauly *et al.*, 2005; FAO, 2009). Consequently, humans now compete directly with marine mammals for resources, with "operational" interactions being the inevitable result (Beverton, 1985; Northridge and Hofman, 1999; Read, 2008). These events include (i) "depredation", where marine mammals damage or remove fish caught in fishing gear (Read, 2005; Gilman *et al.*, 2006; Hamer *et al.*, 2012) and (ii) "bycatch", where marine mammals are incidentally caught when they depredate caught fish or when they fail to see fishing gear when foraging naturally (Hamer and Goldsworthy, 2006; Read *et al.*, 2006; Hamer *et al.*, 2011, 2013). Most bycatch events on longline gear occur when individuals attempt to depredate caught fish, becoming hooked in the process. Participants at a workshop held in Samoa in 2002 concluded that operational interactions with odontocetes had increased globally during the previous 2–3 decades (Donoghue *et al.*, 2003). At the time, solutions were absent from the literature and little was understood about the impact on the marine mammal populations or the fisheries involved.

When depredation occurs in longline fisheries, recorded catch losses per set ranges from 0.5 to 100% (Secchi and Vaske, 1998; Perves *et al.*, 2004; Williams *et al.*, 2007; TEC Inc., 2009; Hamer *et al.*, 2012). The Fiji pelagic tuna longline fishery has reported revenue losses amounting to ∼US$11M annually over the past decade due to pilot whale (*Globicephala* spp.) depredation (Donoghue *et al.*, 2003; Solander, 2013). A similar level of revenue loss has been reported in the Hawaiian tuna fishery, attributable to pilot whale and false killer whale (*Pseudorca crassidens*) depredation (∼US$13M annually; TEC Inc., 2009). Depredation also occurs in demersal longline fisheries at higher latitudes, although to a lesser extent, as demonstrated in the Southern Ocean Patagonian toothfish (*Dissostichus eleginoides*) fishery that losses catch to killer whales *Orcinus Orca* and sperm whales *Physeter macrocephalus* (Roche *et al.*, 2007; Tixier *et al.*, 2010). The additional indirect costs associated with avoidance (e.g. fuel, gear modification and augmentation) may also be high (e.g. Hamer *et al.*, 2012; Peterson and Carothers, 2013; Peterson *et al.*, 2014).

Reports of odontocete bycatch in longline fisheries are also on the increase, likely due to the concomitant rise in the actual frequency of operational interactions and of vessel monitoring and reporting efforts. Reported rates range between 0.002 and 0.231 individuals per set, with short finned pilot whales (*Globicephala macrorhynchus*) and false killer whales being the most commonly involved at lower latitudes (Hamer *et al.*, 2012). The impact on the populations involved remains unclear, although one report from Hawaiian waters suggest that the estimated 7.3 false killer whales bycaught each year in the domestic tuna longline fishery may be responsible for the observed decline between 1998 and 2007 (Chivers *et al.*, 2007; Baird *et al.*, 2008; Baird, 2009). Several odontocete species are reported to have small and genetically isolated populations [e.g. pilot whales in the North Atlantic, Fullard *et al.* (2000); killer whales in Hawaii, Foote *et al.* (2011); common and bottlenose dolphins in southern Australia, Bilgmann *et al.* (2007, 2008)], highlighting their vulnerability to operational interactions with fisheries.

Depredation and bycatch are likely to be numerically underestimated. Depredating odontocetes may deter target fish from taking baited longline hooks simply by being present or they may remove caught fish completely; neither of these outcomes can be detected using conventional methods (e.g. observer programs: Yano and Dahlheim, 1995). This problem likely hinders accurate calculations of stock exploitation and may hinder effective target fish stock management and jeopardise sustainability (Donoghue *et al.*, 2003; Hamer *et al.*, 2012). Similarly, depredating odontocetes that become bycaught may break free of the gear during the soak, before they can be recorded during the haul (e.g. Gilman *et al.*, 2006; Hamer *et al.*, 2013). Some may acquire entanglements or injuries that diminish foraging efficiency or that lead to infections or starvation, both of which are life threatening (e.g. Hucke-Gaete *et al.*, 2004; Forney and Kobayashi, 2007; Baird, 2009; Hamer *et al.*, 2012). Some odontocetes, especially the smaller dolphins and porpoises, may be retained for consumption by crewmembers. Records of these events are scarce, either because there is no documentation framework or because regulations requiring the reporting of interactions often dissuade disclosure due to fear of the potentially negative repercussions (Robards and Reeves, 2011). Both underreporting issues highlight the need to view recorded levels of depredation and bycatch as minima.

Until recently, strategies to mitigate odontocete bycatch and depredation from pelagic longlines have centred on the development of acoustic technologies (Jefferson and Curry, 1996; Hamer *et al.*, 2012). There are a range of associated concerns and limitations that have impeded their ongoing development and use to date. Specific to longline fisheries, passive listening arrays (e.g. McPherson *et al.*, 2008) used to detect odontocetes have proven ineffective for the 10 s of kilometres over which longlines are set and it remains unclear what the most effective response might be if odontocetes are detected anyway (Peterson and Carothers, 2013).

The use of "weak hooks" (i.e. thin wire leaders and grooved hooks) for allowing odontocetes to escape pelagic longlines after becoming bycaught has been explored in Hawaiian and adjacent waters (Bigelow *et al.*, 2012; NOAA, 2012). However, this approach does not address costly depredation events nor the extensive injuries sustained by depredating odontocetes that temporarily ingest hooks. At best, weak hooks allow bycaught odontocetes to escape with injuries of unknown extent and nature, with uncertainty remaining around their fate.

Although having received comparatively little attention, physical deterrence technologies may offer a practical solution. This approach was first explored in the Chilean Patagonian toothfish fishery to mitigate sperm whale depredation from demersal longlines during hauling. A "net sleeve" comprising a large and rigid cage was developed for attachment to individual branchlines on the longline gear, which descended under the influence of gravity and drag during the haul to shroud and protect caught fish (Moreno *et al.*, 2008). Depredation was reduced by 83% (Moreno *et al.*, 2008), providing promise for its broader adaptation to other longline fisheries. In contrast, pelagic longlines may be exposed to depredation by odontocetes during the entire fishing event (Baird *et al.*, 2002; Soto *et al.*, 2008). As such, devices analogous to the net sleeve that are intended for use in a pelagic longline fishery must be necessarily and comparatively complex and lightweight. Specifically, they must allow the baited hook to fish unimpeded "before" a fish is caught, then deploy a deterrent structure "after" a fish is caught to protect it for the remainder of the fishing event.

Given that pelagic longlines are predominantly used to target large tunas, the tension exerted on the branchline when they are caught may be useful for "triggering" deployment of a deterrent structure. There are a number of anecdotal reports of caught fish remaining undamaged in or near tangles in pelagic longline gear. Fishers believe that depredating odontocetes occasionally experience partial or temporary entanglement or minor injury, thus discouraging subsequent approaches (Kock *et al.*, 2006; Hamer and Childerhouse, 2012, 2013). Additionally, depredating odontocetes may need to expend excessive energy during attempts to remove caught fish from within tangled fishing gear. Combining these elements in the development of necessarily lightweight tangle simulating structures may assist in deterring depredating odontocetes, ultimately encouraging them to leave the vicinity of the fishing gear to go in search of more profitable prey elsewhere. In doing so, devices of this nature may also mitigate odontocete bycatch by increasing the distance between odontocetes and fishing hooks and, reducing the risk of entanglement and direct hooking. This outcome would provide a win–win situation for affected fisheries and for affected odontocete populations.

Purpose of this study

In 2009, the Australian Antarctic Division (AAD; a division of the Australian Government Department of the Environment) recognized the need to develop novel and practical methods for mitigating odontocete depredation from pelagic longlines. Initial informal discussions with fishing gear developers and fishers resulted in the preliminary design and manufacture of two devices for deterring depredating odontocetes. They became known as the "chain device" and the "cage device" (Figure 1). Their continued development and subsequent performance assessment occurred in two phases. The first involved a specific flume tank and vessel-based experiments to determine the impact of the devices on longline (i) soak depth and (ii) sink rate, and the second involved extensive sea-trials under full operational conditions to determine the impact of the devices on rates of (iii) target fish catch and (iv) odontocete

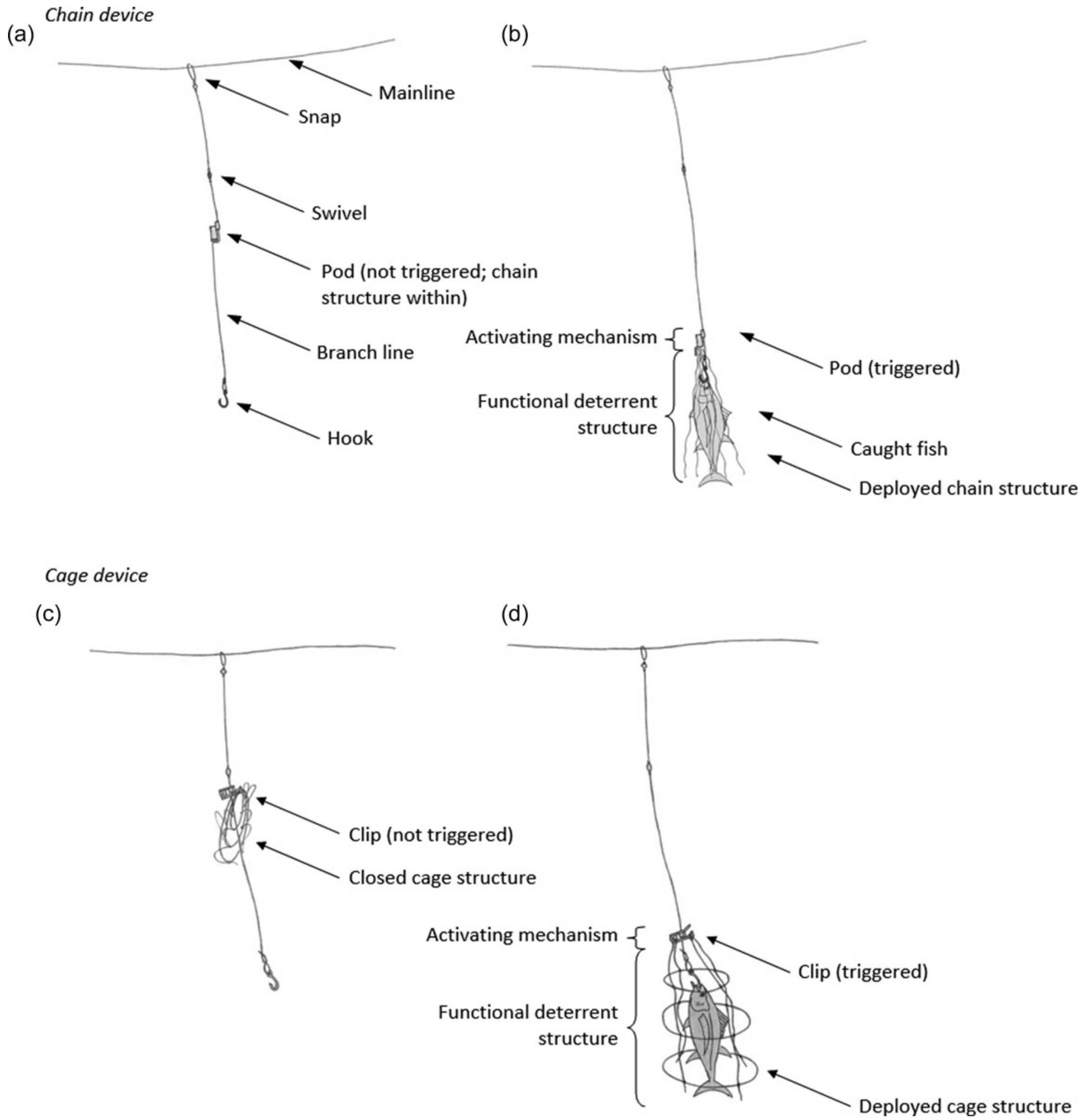

Figure 1. Schematic diagram of the "chain device" and "cage device" (a and c, not triggered; b and d, triggered), both designed to physically deter depredating odontocetes, thus also mitigating the risk of bycatch (updated from Hamer *et al.*, 2012).

depredation and bycatch. Two other factors were of interest due to their potential impact on catch revenue, being (v) fish survival and size and (vi) setting and hauling speed. This study reports on the comprehensive evaluation of these two devices in two fisheries in the western central Pacific Ocean—in Australian and Fijian waters—with a view to providing a platform for further development and adaptation to other pelagic longline fisheries.

Methods

Soak depth of proxy weighted branchlines

During initial informal discussions, fishers raised concerns that increased soak depth caused by the extra weight of the devices could change the suite of tunas and other fish species caught and their catch rates. A researcher accompanied an Australian pelagic longliner to the Coral Sea (northeast Australia exclusive economic zone) in late 2009 during normal fishing operations to assess the impact of the extra weight on the maximum soak depth of the fishing gear. Although the devices were in the early stages of development and prototypes had not yet been produced, it was agreed that the weight of the devices should approximate 120 g. Acting as a proxy for the devices, two 60 g lead weighted swivels were attached approximately half way along the 12 m long branchline, thus approximating the location of an untriggered device (refer to full device description in the "Sink rate of branchlines with prototype devices attached" section).

A conventional pelagic longline set up was used, comprising a "mainline" hung between buoys floating at regular intervals at the surface, with many branchlines hanging from the mainline also at regular intervals between each buoy and generally vertical to the surface. Specifically, a 4 mm diameter monofilament mainline hung between each buoy, separated by a distance of 870 m and commonly referred to as a "section". Attached to each section were 29 1.8 mm diameter monofilament "branchlines" of up to 12 m long, attached at 30 m intervals. In all, 40 sections were deployed each fishing event, measuring a total of 34.8 km.

During each fishing event, a total of 43 weighted swivels were attached to alternate branchlines over three sections, from the buoy marking the beginning of the 12th section to the buoy marking the end of the 14th section. Time–depth recorders (TDRs) were used to record the maximum depth of branchlines with and without weighted swivels. Two types were used, with three units being G5 Long Life (CEFAS Technology Limited, Lowestoft, Suffolk, UK) and five being Mk9 (Wildlife Computers, Redmond, WA, USA). Due to the Mk9s weighing ∼30 g more in seawater than the G5s, one of the 60-g swivels was replaced with a 30-g swivel on branchlines where Mk9s were attached. Five TDRs were attached to branchlines 13–17 in the middle of section 13. The remaining three TDRs were attached to branchlines 14–16 in the middle of section 19. Section 19 was four sections away from the closest weighted section (section 14), thus providing a comparison of the soak depth between weighted and unweighted sections. To ensure the additional weight of caught fish did not confound the results, none of the hooks in sections 12–14 and 19 were baited. The middle of a section will likely sink the furthest, due to the catena of the mainline between the buoys caused by the weight of the gear; this is likely to vary according to the effect of wind, tide, and current.

Device design and development

Both devices contained an activating mechanism and a deterrent structure (Figure 1), which set them apart from the comparatively rigid and simple net sleeve used in the Patagonian toothfish fishery (Moreno *et al.*, 2008). Each was designed to attach to a branchline each time the gear was set and was placed half way along the mainline to remain well clear of the baited hook so as not to impede its fishing efficiency. The devices were held in place by routing the branchline through a "dog-leg" or directional change on the activating mechanism that was forced to straighten (i.e. "trigger") and thus release the deterrent structure when a caught fish applied tension by pulling on the hook (Figure 2). The deterrent structure then descend towards the caught fish under the influence of gravity. A one way cam system was also included to ensure the triggered deterrent structure could not move away from a caught fish if it swam above the mainline and consequently inverted the branchline. The deterrent structure of the chain device comprised two 1500 mm stainless steel chains, with a link size of 7 × 16 mm and wall thickness of 2 mm. The deterrent structure of the cage device comprised fishing gear readily available on the vessel to construct a cone-like shape; three 450 mm loops of monofilament nylon mainline of 3.1 mm and four 900 m side lengths of 1.9 mm diameter branchline, joined with aluminium swages. Although prescribed for this study to ensure comparability during experimental sea trials, the chain and cage device deterrent structures could be altered to suit-specific requirements in other fisheries.

The activating mechanism of the chain device was collaboratively designed by the AAD and Fishtek Limited (Devon, UK), with components manufactured by Fishtek and 3D Systems Asia Pacific (Victoria, Australia). The activating mechanism of the cage device was entirely developed by the AAD (DJH and SJC) and manufactured by 3D Systems Asia Pacific. The ownership of intellectual property and associated development and production of both devices is vested under licence exclusively to the Australian Government.

Sink rate of branchlines with prototype devices attached

Although being developed for and trialled in a tropical pelagic longline fishery where seabirds are seldom if ever seen, it was deemed prudent to determine the possibility of increased risk of seabird bycatch to inform the impact of their use in areas where the two overlap. The first prototypes of both device designs were ready for preliminary testing in late 2010. The overall apparent weight in seawater of the complete chain device was ∼175 g and of the cage device was

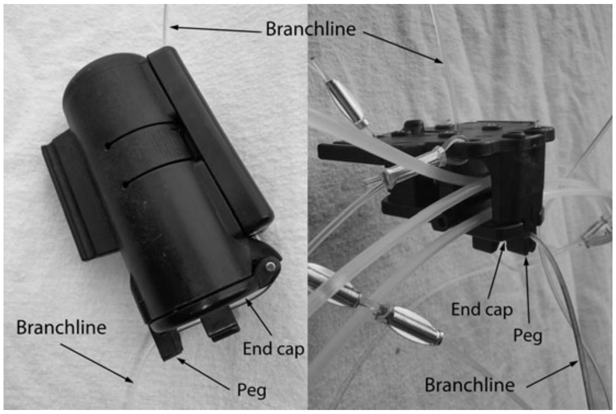

Figure 2. Detail of the trigger assembly on the chain device (left) and cage device. When a fish is caught, the branchline is pulled straight, pulling free of the peg, and opening the end cap, which in turn releases the deterrent structure.

~145 g. Despite both device designs being heavier than originally predicted, the fishers involved in the sea trials remained concerned that the extra drag caused by the surface area of the devices and propeller wash near the surface might slow the sink rate of hooks as the gear it is set, thus increasing the risk of seabird bycatch (e.g. Robertson *et al.*, 2006).

The Circulating Water Channel (CWC; Australian Maritime College, Beauty Point, Tasmania, Australia) allowed controlled horizontal water speeds for accurate comparisons of branchlines with and without devices attached under simulated operational conditions. Despite the CWC being only 2.5 m deep, three 6 m long branchlines were used, with one of each device attached 4 m above the hook end (i.e. the "treatments") and the third without a device (i.e. the "control"). A 60-g lead fishing sinker was attached at the bottom end of each to simulate a baited hook. The top end of each branchline was attached to a stationary observation carriage at 1.5 m above the surface of the water. Given that maximum albatross dive depth ranges between 4.5 m for black browed albatross (*T. melanophrys*; Prince *et al.*, 1994) and 7.4 m for shy albatross (*T. auta*; Hedd *et al.*, 1996), the CWC represented the upper 34–56% of those depths.

Three G5 TDRs were used, one on each branchline, to record sink rate profiles and were attached immediately above each device on the two treatment branchlines and at the same position on the control branchline. The TDRs measured depth at 1 s intervals so that a vertical profile for each instrumented treatment and control branchline could be calculated. Each of the three branchlines were manually released from the observation carriage simultaneously at 1 m above the surface of the water, then retrieved after coming into contact with the bottom of the tank. In all, 100 replicates were obtained for each of the three horizontal water speeds, being 0 m s^{-1}, 0.5 m s^{-1} (0.97 knots) and 1 m s^{-1} (1.94 knots).

Sea-trial experimental design and data collection

The sea trials for assessing the efficacy of the two devices in mitigating odontocete depredation and bycatch were conducted on eight trips using seven commercial pelagic longliners between December 2010 and July 2013. Two occurred in the Australian EEZ (principally in the Coral Sea) and six occurred in the Fijian EEZ (principally in waters to the south and east of Viti Levu and to the north of Vanua Levu). Typically, 28–35 branchlines of 6–12 m long were attached to the mainline at a distance of ~30 m from each other in each section (i.e. between each buoy). Up to 40 sections of the gear were deployed during each fishing event, with the overall mainline length being 33.6–42 km long. Although the gear used on the longline of a given vessel was typically consistent in configuration, it was not possible to influence the configuration to achieve consistency between vessels due to skipper concerns about the possible negative effect on fish catch rates. Up to 250 chain and 250 cage devices were deployed each set and were attached to alternate branchlines; a cage device (treatment) on a branchline, nothing on the next (control), a chain device on the next (treatment), nothing on the next (control), etc. (Figure 3). Using this configuration, up to 1000 branchlines were deployed in what was termed the "device series" (DS). A second "non-device series" (N-DS) was set, before or after the DS, in which up to 1000 branchlines were deployed without devices and effectively all being controls. The depth of the catena in each section between each buoy ranged between 30 and 300 m, and although fish catch composition is thought to vary with depth (e.g. Kerstetter and Graves, 2006), the alternate placement of devices on branchlines across these depths and the large number of sections involved will likely nullify any depth-related catch bias.

The underlying basis for using the devices was to deter depredating odontocetes and by default mitigate the likelihood of bycatch, while having no effect on target fish. In the DS, fish catch and depredation rates on treatment and control hooks were compared to determine if target fish are deterred from taking a baited hook by an untriggered device and if depredating odontocetes were deterred from taking a caught fish by a triggered device; see the "Catch rate data analyses" section for statistical analyses procedure. However, results obtained from DS data alone did not assist in understanding the impact of the devices on fish catch and depredation rates on adjacent control hooks; the "edge effect". This element could be determined by comparing catch and depredation rates on the control branchlines in the DS with rates on branchlines in the N-DS, with the latter effectively being all controls. Additionally, it was deemed that a favorable "feeding choice" may have taken place when fish were caught on consecutive hooks with an alternating presence of deployed devices in the DS, where the unprotected fish was depredated and the protected fish was not.

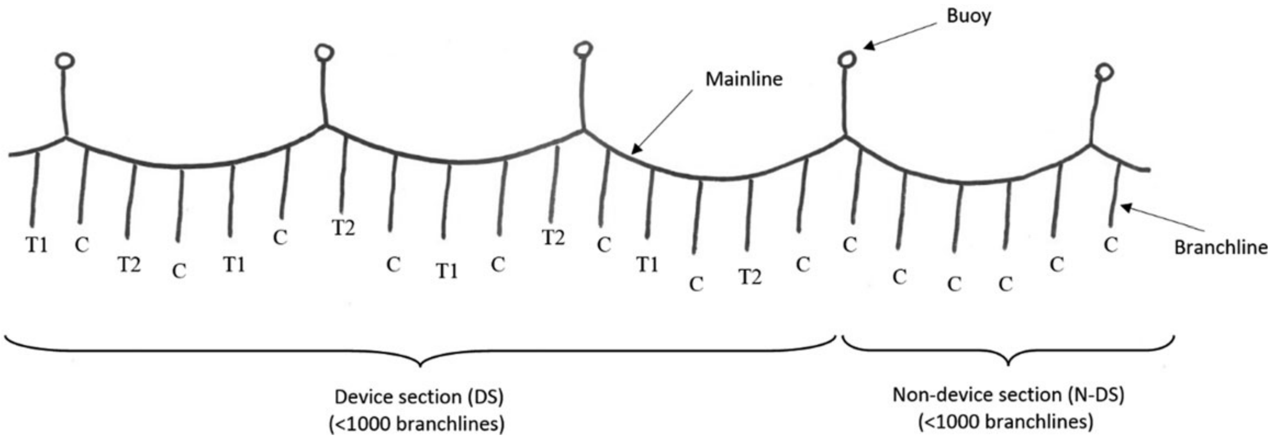

Figure 3. Schematic diagram, not to scale, of pelagic longline configuration used during sea trials, depicting the treatments [chain device ("T1") and cage device ("T2")] and control ("C") in the DS and the control branchlines ("C") in the N-DS. The control branchlines in the DS were the same as the control branchlines in the N-DS.

An on-board independent observer collected data during each fishing event. When the gear was set, typically commencing at dawn, the observer recorded (i) the location of the fishing event, (ii) setting duration, (iii) bait type, and (iv) presence of visible odontocetes. When the gear was hauled, typically commencing late afternoon, the observer recorded (v) hauling duration, (vi) fish species and number, (vii) their size and life state, (viii) incidence and possible perpetrator of depredation damage to caught fish, (ix) number of odontocetes bycaught and their life state, and (x) the occurrence of device non-deployment or damage when a fish was caught. Data collected on elements (vi)–(x) were recorded for each branchline and recorded whether a chain or cage device were attached. For the purposes of determining the performance of the devices in protecting fish from odontocete depredation, data collection was confined to the five most often caught target species, being albacore (*Thunnus alalunga*), yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*), mahi mahi (*Coryphaena hippurus*), and wahoo (*Acanthocybium solandri*). Attributing species or taxa of potential depredators to the damage observed on caught fish followed forensic techniques employed on injuries to humans (following Bertino, 2008) and their application to marine predators (following Hamer and Sumner, in press).

Catch rate data analyses

Fish catch rates were modelled by applying a generalized linear mixed model (GLMM; following Breslow and Clayton, 1993; Bolker *et al.*, 2009) to the number of fish caught each fishing event for the five most abundant fish species caught across all fishing events. Initially, a Poisson rate model was assumed, with an offset applied equal to the logarithm of the total number of hooks per set. The accuracy of this type of model improves with more observations (i.e. hooks) in each treatment category in each set and uses the observed catches as the response variable. Model development involved first fitting with fixed effects for "treatment" (four levels: cage device, chain device, DS control, and N-DS control) and "species" (five levels: albacore, yellowfin, bigeye, mahi mahi, and wahoo), and the interaction between the two. A random effect (RE) for "trip" was included to account for several uncontrolled factors, including sampling time (year and month), location, and vessel. Data were excluded from the analyses if the devices or gear associated with a branchline had malfunctioned in any way (e.g. the device had failed to deploy when a fish was caught or a control branchline had become wrapped around the mainline). This approach was found to be overdispersed when examined by residual analysis and by an approximate test of the ratio of squared Pearson residuals to the residual degrees of freedom, assuming each variance/covariance parameter as one model degree of freedom. Two alternative GLMMs, each with the same fixed effects, were considered in the presence of significant overdispersion and found to be adequate. The first alternative included an observation-level (i.e. "set") RE in addition to a "trip"-level RE (following Maindonald and Braun, 2010), whereas the second included a "trip"-level RE only but assumed a negative binomial error distribution with log-link function (Zuur *et al.*, 2009). Overdispersion was again examined, with the second model (negative binomial) selected due to the marginally lower Akaike's Information Criterion (AIC) value (Akaike, 1974). Model simplification of fixed effects was by backward selection based on likelihood ratio tests. All analyses were conducted in version 3.0.1 of the R environment for statistical computing (R Core Development Team, 2013), using the linear mixed-effects models package lme4 version 1.0-5 (Bates *et al.*, 2013).

Results

Effect of prototype devices on the sink rate and proxy weights on soak depth

The sink rates of the two branchlines containing the two prototype devices and the one branchline that remained unmodified were recorded at all three horizontal water speeds. Branchlines with devices attached sank more slowly than branchlines without (the control), with the cage device being the slowest to sink (Figure 4). Control branchlines sunk vertically at 0.90 ± 0.21 m s^{-1} at a horizontal water speed of 1 m s^{-1} (Table 1). The chain and cage device sunk at 0.56 ± 0.25 and 0.37 ± 0.17 m s^{-1} at a horizontal water speed of 1 m s^{-1}, respectively, or at 62 and 41% the sink rate of a control branchline, despite the truncated depth of the CWC. Vertical sink rates for each of the three branchlines increased slightly at slower horizontal water flow speeds. Despite the slower sink rate of device branchlines, observations indicated that the presence of the devices did not affect the general behaviour of branchlines, which sank in the same manner as the control branchline, without exhibiting any detectable oscillation or rotation.

Eleven longline fishing sets were undertaken to assess the impact of the devices on soak depth, using lead weighted swivels as a proxy. Branchlines with attached weights in section 13, which is analogous to the DS in the sea trials, sunk to depths of 257.64 ± 11.71 m. Branchlines without attached weights sank to 254.90 ± 12.56 m in section 13 and to 247.36 ± 12.84 m in section 19, the latter being analogous to the N-DS in the sea trials (Figure 5). Analyses (ANOVA) indicated that the depths between weighted and

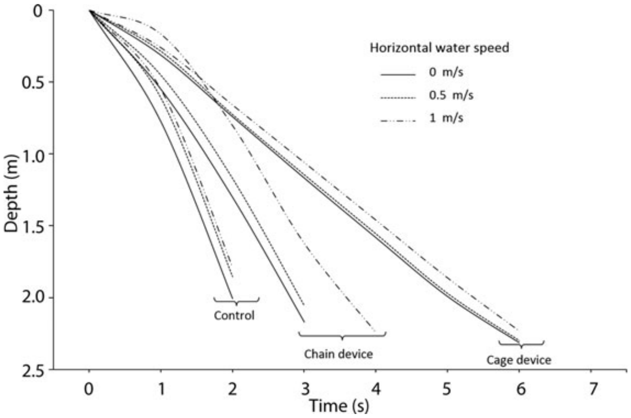

Figure 4. Summary of branchline sink rates with and without devices attached in the 2.5 m deep AMC CMC (flume tank), at three horizontal water speeds.

Table 1. Summary of branchline sink rates of pelagic longline branchlines with devices attached (the treatment) and without devices attached (the control), in the Australian Maritime College (AMC) Flume Tank (Tasmania, Australia), at three horizontal water speeds.

	Horizontal water speed (m s^{-1})		
	0	**0.5**	**1**
Sink rate (m s^{-1})			
Control	1	0.93	0.90
Chain	0.39	0.38	0.37
Cage	0.72	0.69	0.56

unweighted gear in section 13 were not significantly different ($p = 0.88$), nor were depths of adjacent unweighted branchlines significantly different from unweighted branchlines in section 19 ($p = 0.68$).

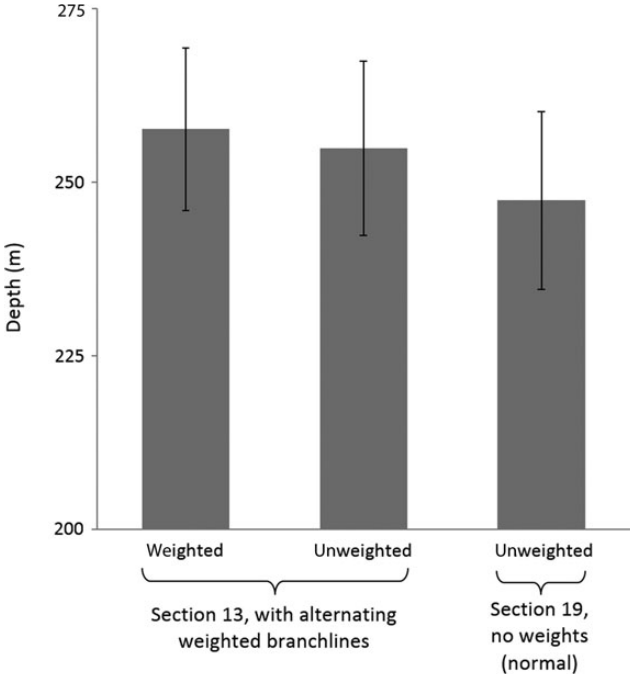

Figure 5. Comparative soak depth of weighted (using 120 g of lead) and unweighted branchlines, the former being a proxy for device weight. The unweighted branchlines comprise two groups: those next to weighted branchlines in section 13 and all unmodified and unweighted branchlines in section 19.

Effect of the chain and cage devices on target fish catch rate, survival, and size

Data were collected from the Australian and Fijian regions (17 and 83%, respectively), from seven vessels over eight trips (Figure 6). This amounted to 94 sets and fishing days, with data for 116 768 functional branchlines being recorded. A further 3116 branchlines (2.6%) failed in some way (e.g. the swivel had parted and the lower half of the branchline was missing, or the hook had broken away and was missing) and thus were excluded from the data. These also included 240 with devices attached (see the "Device non-deployment and damage when fish caught" section below for details). All hooks were baited with sardine and 16 identifiable fish species were caught, with albacore, yellowfin, bigeye, mahi mahi, and wahoo being caught most often (23.77, 14.72, 3.85, 13.49, and 9.46% of the overall catch, respectively). Comparatively, low value skipjack tuna (*Katsuwonus pelamis*), barracuda (*Sphyraena* spp.), rudderfish (*Centrolophus niger*), billfish (marlins and sailfish: Istiophoridae), and lancet fish (*Alepisaurus* spp.) accounted for most of the remaining 34.71% of caught fish.

Catch rates for the five most abundant and high value species were pooled for statistical comparisons between control groups in the DS and N-DS, because the likelihood ratio test indicated a non-significant interaction effect ($\chi^2_{12} = 18.6$, $p = 0.1$); there was minimal difference in the impact on catch rates caused by the devices across the five species. Statistical comparisons of fish catch rates on DS chain, cage, and control branchlines indicated that there was no significant difference between them (Table 2). However, inclusion of N-DS control branchlines revealed the catch rate that was significantly lower when compared with DS chain, cage, and control branchlines (Table 2; Figure 7).

Except for the first trip in the Australian EEZ, fish survival and size were also recorded. Survival was significantly higher in only 3 of the 20 cases where direct comparisons were made between control branchlines in the DS and N-DS (Figure 8). Specifically, fish survival on branchlines with chain devices

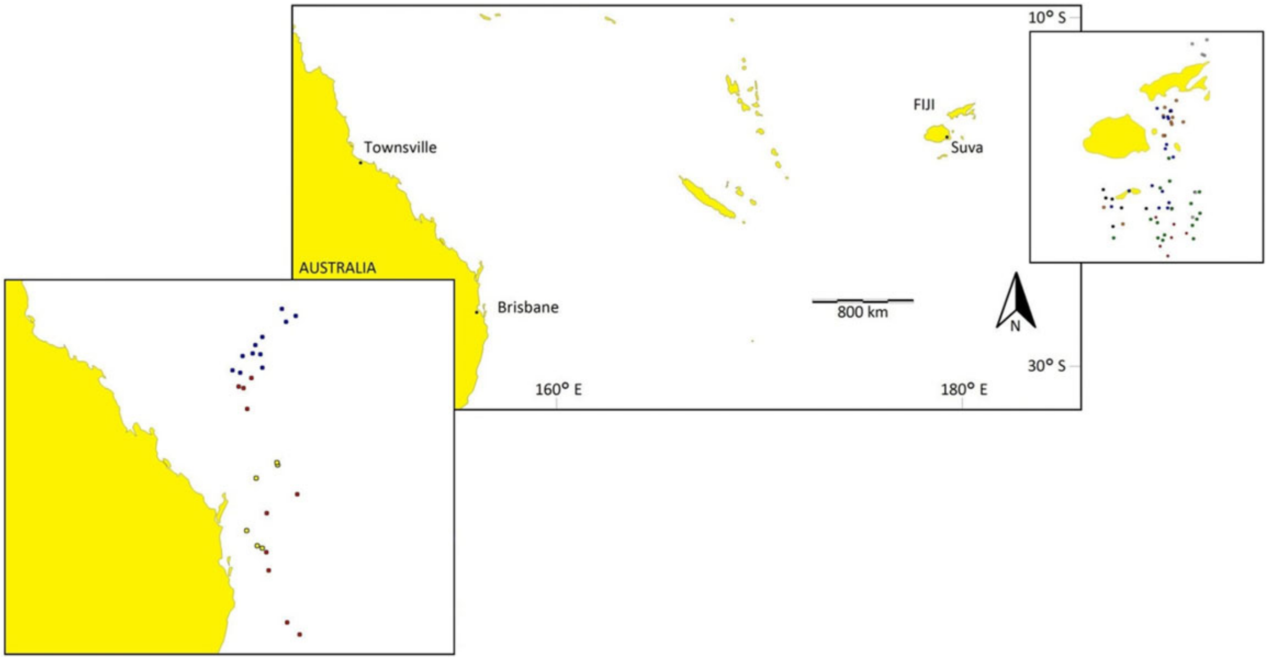

Figure 6. Map of south Pacific region, showing distribution of fishing effort during sea trials in the Australian and Fijian EEZs.

Table 2. Results of the GLMM of the impact of the devices on the target fish catch rate

	Estimate	SE	*t*-value	Pr(>|z|)
DS only				
DS Control (intercept)	−3.71	0.17	−21.79	$<2e^{-16}$
DS Chain	0.17	0.11	1.54	0.12
DS Cage	0.15	0.11	1.36	0.17
N-DS and DS				
N-DS Control (intercept)	−3.95	0.19	−21.04	$<2e^{-16}$
DS Control	0.22	0.11	2.02	0.0430
DS Chain	0.40	0.12	3.46	0.0006
DS Cage	0.38	0.12	3.28	0.0010

Two alternatives are shown: (i) the DS only, with the DS control as the intercept (showing no significant differences to chain and cage) and (ii) all the gear which also includes the N-DS, with the N-DS control as the intercept (showing marginal significant difference to DS control and marked significant difference to chain and cage).

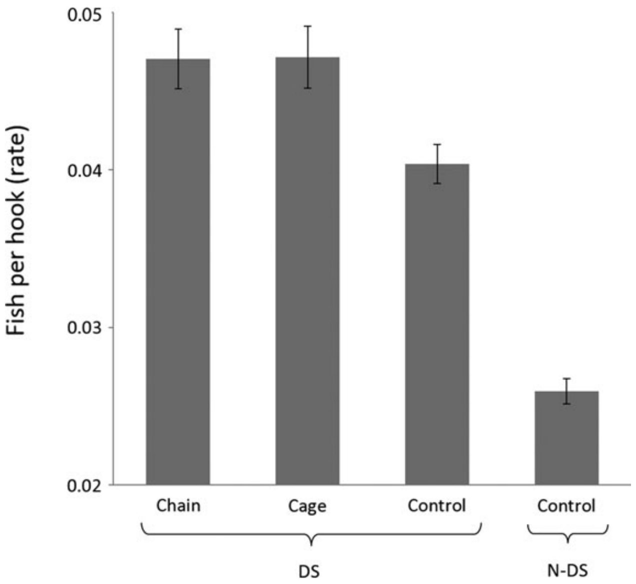

Figure 7. Overall fish catch rates on branchlines with the chain and cage device (treatments, protected) and branchlines without devices attached (control, unprotected) in the DS and on branchlines (all controls, unprotected) in the N-DS.

attached was significantly higher than on control branchlines in the DS for only one of the five most abundant species caught (bigeye, $p = 0.01$) and on branchlines with cage devices branchlines than on controls in the DS for two of those species (yellowfin, $p = 0.03$; bigeye, $p = 0.03$). Mean survival was only significantly higher for one species (mahi mahi: $p = 0.05$), while there was no clear difference in survival between DS and N-DS control branchlines. The mean fish length of the five most often caught fish species was not statistically significantly different on branchlines with a device attached compared with controls in the DS and N-DS (Figure 9).

Odontocete depredation and bycatch

There were 27 depredation events attributable to odontocetes over eight sets, of which 24 (88.89%) occurred on unprotected control branchlines and 3 occurred on treatment branchlines, despite fish catch rates being similar between the two groups. All five fish species of interest were depredated, with albacore being the most affected (55.56% of all depredated fish), followed by mahi mahi (18.49%), yellowfin (14.81%), bigeye (7.44%), and wahoo (3.73%). On the three occasions where depredation occurred on a treatment branchline, the attached device failed to deploy, suggesting that it behaved like a control branchline where caught fish remain unprotected. The circumstances leading to deployment failure remain unclear, although on one occasion the branchline was tightly tangled around the mainline and on the other two occasions the remains of the caught fish suggested that it was too small to apply sufficient tension to trigger the device. At least two fish were caught consecutively on 7 of the 27 occasions. During each, the fish on the unprotected control branchline was depredated, whereas the fish caught on the adjacent device protected branchline was not. Interestingly, odontocetes were not observed before, during, or after sets where depredation was recorded, although pilot whales were observed on several days when depredation was not recorded.

Many other depredation events were attributed to cookie-cutter sharks (*Isistius brasiliensis*) and larger pelagic sharks (possibly oceanic white tip *Carcharhinus longimanus*, blue *Prionace glauca*, and hammerhead *Sphyrna* spp., based on the species landed), accounting for 10.21 ± 1.90 and 1.49 ± 0.39%, respectively, of depredation in the overall fish catch, compared with 0.88 ± 0.30% for odontocetes. As with catch rates, depredation rates for the five species were pooled for statistical comparisons between treatment and control groups in the DS and N-DS, because the likelihood ratio test of differences proved non-significant ($\chi^2_{48} = 61$, $p = 0.1$). Similarly, the interaction term could also be removed ($\chi^2_6 = 4.21, p = 0.7$). Depredation on N-DS controls was not significantly different from depredation on DS controls, although both were significantly higher than depredation on DS chain and cage device branchlines (Figure 10). Although bait depredation also occurred, it was not possible to attribute it categorically to a specific species or taxa; detailed inspection of damaged bait suggested that small pelagic fish or squids were most likely responsible.

Four odontocetes were bycaught and released alive during the study, with three being false killer whales (two in Australia and one in Fiji) and one being a melon-headed whale (*Pepanocephala electra*; in Fiji). All occurred on control branchlines (one in the DS and three in the N-DS). When released, each retained the hook and a part of the branchline, due to difficulty in bringing them alongside the vessel. The hook was not visible in all four cases and the visible length of the branchline suggested that it was embedded either in the lip or deeper in the mouth or stomach. Blood was visible in the water on all four occasions. The post-release fate of each released animal was not documented. Individuals of both species were not observed at any other time. Pilot whales were observed on several occasions at a distance from the vessel during fishing events where no bycatch was recorded.

Device non-deployment and damage when fish caught

Of the 1125 fish observed caught on branchlines with devices attached in the DS, successful device deployment occurred on 885 (78.67%) of occasions. Specifically, chain and cage devices deployed on 466 (80.21%) and 419 (77.02%) occasions, respectively. As indicated in the “Catch rate data analyses” and “Effect of the chain and cage devices on target fish catch rate, survival, and size” sections above, observations involving failed device deployment or failed deployment of control branchlines were excluded from the data and statistical analyses. The proportion of devices that successfully

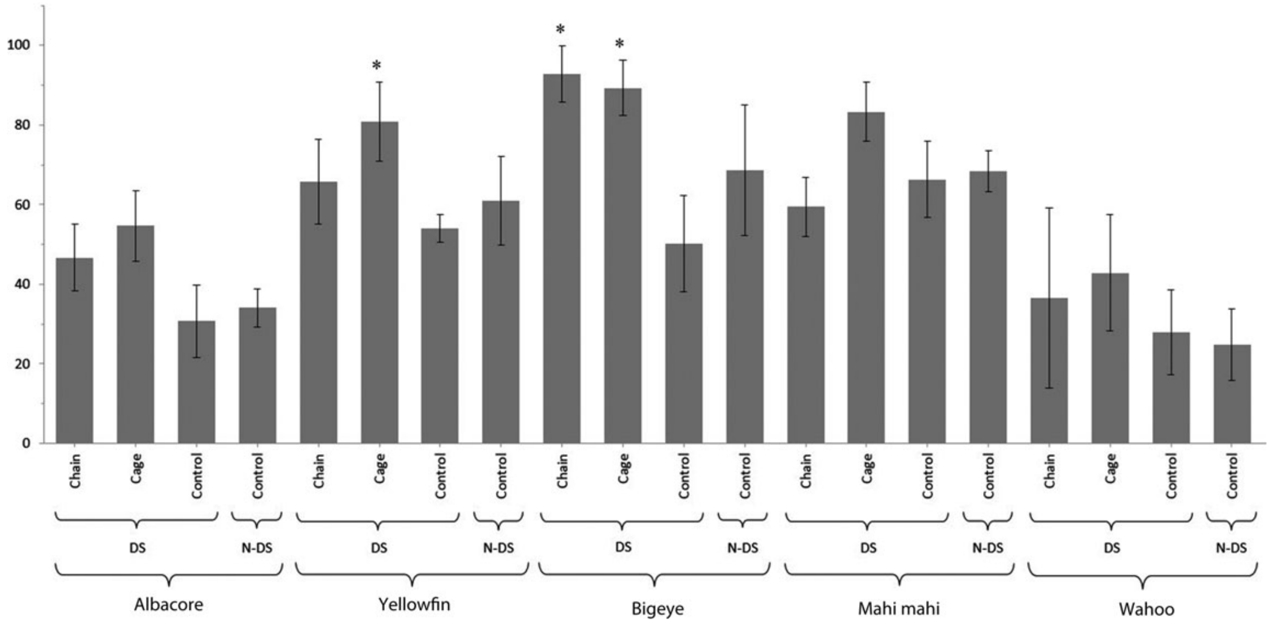

Figure 8. Mean survival (%; by vessel/trip) of the five most frequently caught fish species in the DS [branchlines with the chain and cage devices (treatments, protected) and branchlines without devices attached (control, unprotected)] and in the N-DS [all branchlines without devices attached (all controls, unprotected)], during sea trials on pelagic tuna longlines in Australian and Fijian waters. Asterisks indicate the survival rates on treatment branchlines statistically significantly higher than on corresponding control branchlines.

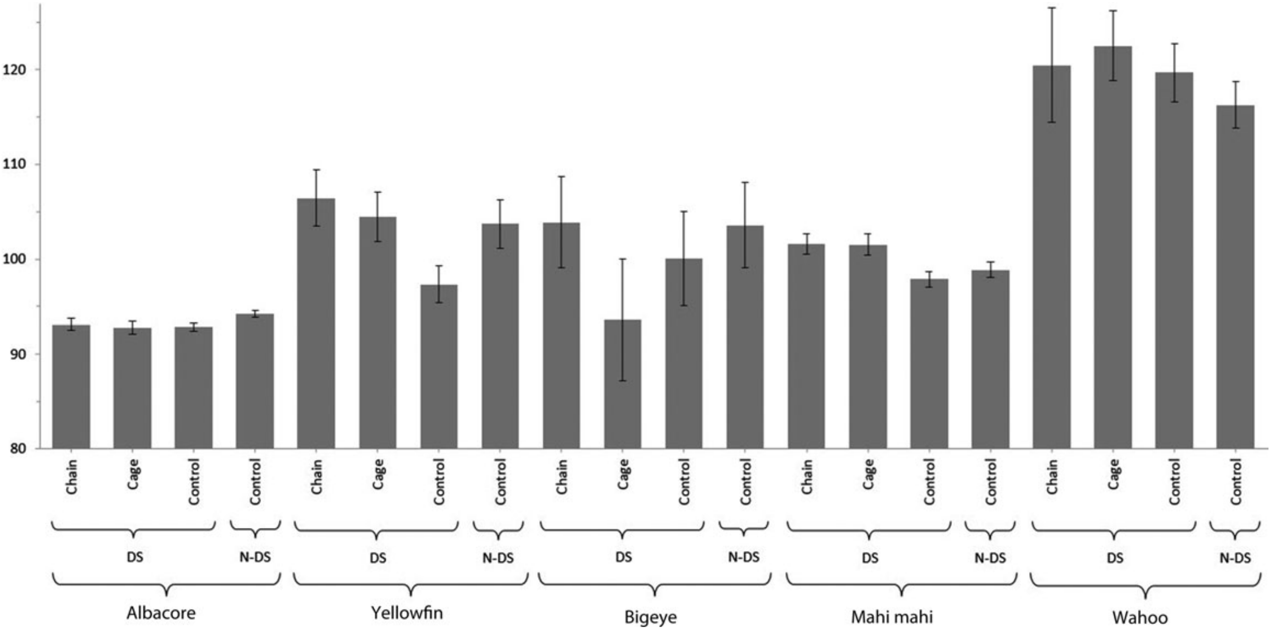

Figure 9. Mean length (cm; by vessel/trip) of the five most frequently caught fish species in the DS [branchlines with the chain and cage devices (treatments, protected) and branchlines without devices attached (control, unprotected)] and in the N-DS [all branchlines without devices attached (all controls, unprotected)], during sea trials on pelagic tuna longlines in Australian and Fijian waters.

deployed when a fish was caught varied between sets. For chain devices, 75–100% success occurred 59% of the time, 50–75% success occurred 26.9% of the time, and <50% occurred 14.1% of the time. For cage devices, 75–100% success occurred 55.7% of the time, 50–75% success occurred 30.4% of the time, and <50% occurred 13.9% of the time. Devices failed to deploy for three identifiable reasons. First, the caught fish did not exert sufficient tension to trigger the device to facilitate deployment of the deterrent structure, because it was too small or was a species that tended not to pull hard when caught. Second, some caught fish tended to swim around the mainline several times before pulling on the branchline and triggering the device, by which time it was unable to deploy because it had become wrapped around the mainline. Third, incorrect adjustment of the tension release threshold on the activating mechanism

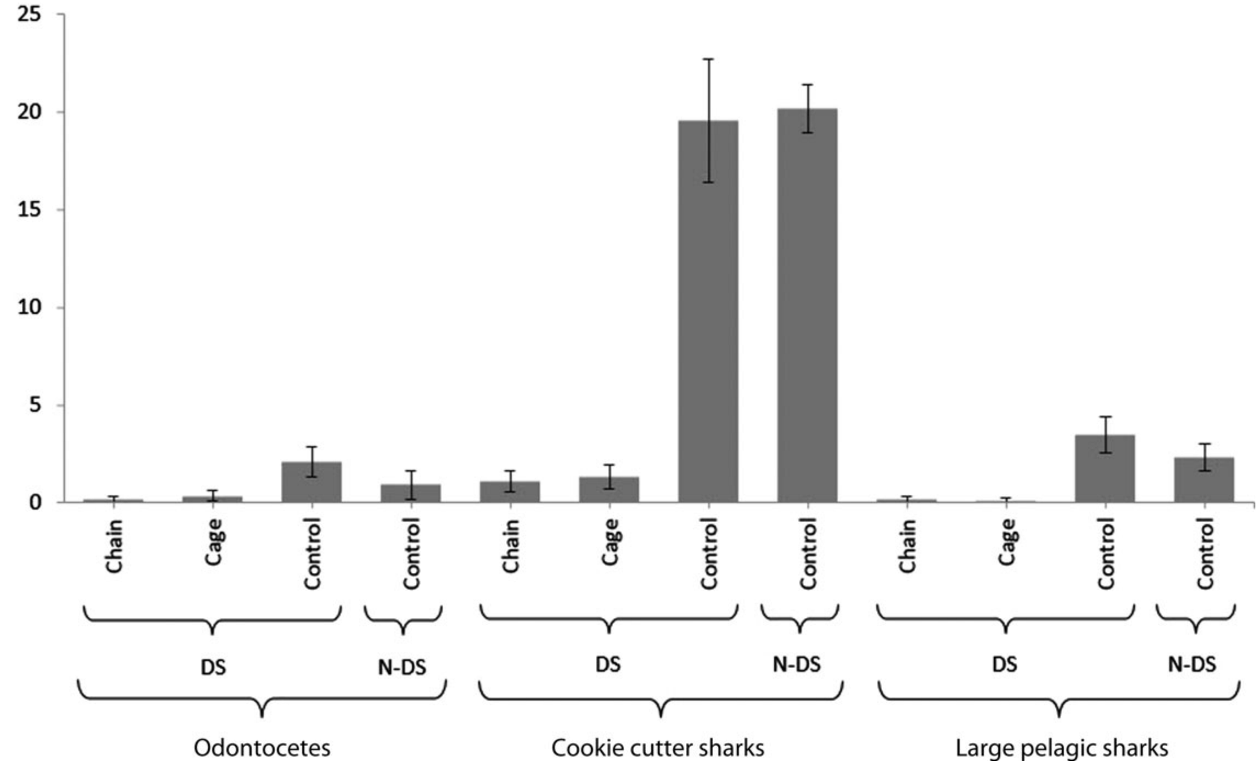

Figure 10. Overall percentage of fish depredation on branchlines (by vessel/trip) with a chain device or cage device (treatment, protected) in the DS [branchlines with the chain and cage devices (treatments, protected) and branchlines without devices attached (control, unprotected)] and in the N-DS [all branchlines without devices attached (all controls, unprotected)], during sea trials on pelagic tuna longlines in Australian and Fijian waters.

resulted in the need for tensions more than those exerted by caught fish to release the deterrent structure.

Chain devices were damaged on 28 or 4.82% of occasions when fish were caught, whereas cage devices were damaged on 47 or 8.64% of occasions. These are included among those that failed to deploy. Damage occurred for three identifiable reasons. First, caught fish sometimes thrashed or swam around the mainline, often resulting in the chain or cage material of the deterrent structure becoming wrapped up by the branchline and damaged. This was especially true for the comparatively delicate cage device. Second, excessive or frequent impact with the hull or deck during setting and hauling operations sometimes resulted in component failure in the activating mechanism, especially on the heavier chain device. Third, harsh marine conditions resulted in extensive corrosion of the 304 grade stainless steel components that were used in the hinges, pins, and bolts of some units.

Impact on setting and hauling times

Generally, setting times were fixed at 6–8 s intervals, depending on the protocol adopted by the vessel master to ensure the branchlines were placed at the prescribed distance of ~30 m between each along the mainline. The assistance of an additional crewmember was needed during the set to hand the devices to each of the two crewmembers tasked with attaching the branchlines at the stern of the vessel. In contrast, hauling time was generally slower in the DS (mean, 20.57 ± 0.69 s branchline^{-1}) compared with the N-DS (mean, 17.47 ± 0.65 s branchline^{-1}). This was significant ($p = 0.03$) and individual vessel analyses suggested that this was attributable to two of the seven vessels used ($p = 0.02$ and $p = 0.01$), thus may not typify the impact of devices on hauling times. Similar to setting, an additional crewmember was also required during the haul to receive the devices from the two crewmembers normally tasked with detaching the branchlines. Repacking of devices that deployed when a fish was caught was managed on all but those two vessels by the extra crewmember during the time interval between each branchline coming aboard.

Discussion

Efforts to mitigate odontocete bycatch through gear modification are widespread across fishing methods, such as purse-seine (Gosliner, 1999; Hamer *et al.*, 2008), trawl (Zeeberg *et al.*, 2006), and trap (Meyer *et al.*, 2011). Two studies to assess depredation mitigation methods have recently occurred in longline fisheries, with one in a demersal longline fishery in Chile (Moreno *et al.*, 2008) and another in a pelagic longline fishery in the Seychelles (Rabearisoa *et al.*, 2012). The former study underpinned the development of concepts and designs in this study, although the need to develop comparatively lightweight and complex devices to prevent depredation during the soak prevented its direct adaptation. Despite the latter study being in a pelagic longline fishery and adopting a similar approach to the one explored in this study, its undertaking only become apparent to the authors after both studies had concluded. Nonetheless, this study placed greater emphasis on operational integration, because proving efficacy alone may be insufficient to encourage voluntary use by fishers. Given that regulatory compliance can be costly or difficult to implement, incentives to use this type of technology are underpinned by ensuring its ease of use aboard the vessel, as well as by the economic gains that should arise from its use through the mitigation of depredation and negligible impact on fish catch rates.

Minimal impact on fishing operation

From a conservation perspective, the inclusion of devices on branchlines reduced the sink rate of the fishing gear, which is of concern in pelagic longline fisheries operating at higher latitudes that overlap with albatrosses and petrels (e.g. Robertson *et al.*, 2013; Melvin *et al.*, 2014). Buoyancy caused by air retention, drag, and propeller wash may extend the period that baited hooks remain near the surface and within seabird diving range (e.g. Prince *et al.*, 1994; Hedd *et al.*, 1996). Addressing this potential problem was not a focus of this study, because seabird bycatch did not occur at the lower tropical latitudes where the sea trials occurred. Nonetheless, the addition of weight to increase sink rates should be considered if these or similar devices are to be used in areas where seabird bycatch is a possibility. Despite the caveats on the sink rate, soak depths were not significantly affected by the addition of devices, offering encouragement to longline fishers who typically set gear at prescribed depths to target specific species (e.g. Galeana-Villasenor *et al.*, 2008; Campbell and Yong, 2012).

Importantly for longline fishers, the devices had a positive impact on target fish catch rates, with higher rates reported on device branchlines in the DS compared with control branchlines in the N-DS. This suggests that either more fish were attracted to the vicinity of the devices or more depredators were deterred. A recent Falkland Island (UK) study reported that some fish species are attracted to analogous structures on demersal longlines (Brown *et al.*, 2010). Additionally, the significantly higher catch rate on DS control branchlines compared with N-DS control branchlines suggests an "edge effect". Odontocete species widely exhibit rapid learning capacity (Wursig, 2002; Schakner and Blumstein, 2013) and may quickly associate the simulated tangle of the deterrent structures that shroud the caught fish with prior negative experiences. This may encourage depredating odontocetes to move away from the device, either in the direction of the adjacent unprotected branchlines in the N-DS, or away from the area altogether (e.g. Kock *et al.*, 2006). This outcome has two positive economic implications. First, using the devices may directly increase revenue through increased catch rates. Second, the cost of implementation may be halved, because the spatially extended influence of the devices suggests that only every second branchline need be fitted with a device.

The size of caught fish also remained largely unchanged between the two treatment and the two control groups, although survival significantly increased in three comparisons involving bigeye on chain and cage devices and yellowfin on cage devices. Observations ranged between 39 and 125 across the comparisons, suggesting that they were representative. The effect of stress caused by the presence of the devices may be less than that caused by the presence of depredating odontocetes, thus resulting in the caught fish remaining alive for longer in situations where odontocetes have been deterred.

An extra crewmember was needed for setting and hauling to ensure the timely attachment and detachment of devices during setting and hauling. Although hauling was significantly slower when involving devices, this may not have been representative because the results were attributable to just two of the seven vessels involved in the study. Nonetheless, the cost associated with employing an extra crewmember may be prohibitive in situations where the economic benefits through the increased catch rate are not obvious.

The similar study conducted in Seychelles had a similarly positive outcome, although the fishers involved were also initially concerned about the impact of using the analogous devices (Rabearisoa *et al.*, 2012). Nonetheless, the present study, along with the Seychelles and Chilean studies, provides growing evidence that augmenting conventional pelagic longline gear with devices to physically deter depredating odontocetes and other taxa can occur with minimal impact on regular fishing activities, both operationally and economically.

Promising reduction in depredation

Depredation levels reported in this study were very low, despite the various reports of economically worrisome levels elsewhere (e.g. Gilman *et al.*, 2006; IOTC, 2007; Ramos-Cartelle and Mejuto, 2008; Hamer *et al.*, 2012; Peterson *et al.*, 2014). The vast majority of observed depredation occurred on unprotected control branchlines, with the few that did occur on treatment branchlines being attributable to device failure. Although the mechanism for deterring odontocetes remains unclear, the results of this study indicate that they may be discouraged from approaching caught fish protected by the tangle simulating deterrent device. Additionally, the several reported instances where an unprotected fish was depredated next to a protected and undamaged caught fish suggests that favorable feeding choice may have occurred, further supporting the premise that depredating odontocetes avoid gear tangles. Nonetheless, observed depredation should be considered a minimum estimate of the actual level, because an unknown proportion of caught fish were likely removed altogether.

The benefits of using such devices to mitigate depredation may extend beyond the economic advantages of the vessels that use them. Effective fishery management may be hindered by the activities of depredating odontocetes, with the potential for overfishing to occur in the short term, due to the discard of large numbers of depredation damaged fish and due to depredating odontocetes completely removing caught fish. The omission of these two groups of caught fish from catch records will negatively biases official catch records, resulting in an underestimate of exploitation levels (Hucke-Gaete *et al.*, 2004; Hamer *et al.*, 2012). This situation is problematic for domestic and inter-governmental agencies aiming to sustainably manage fisheries at a time when many fisheries are overfished or depleted (Pauly *et al.*, 1998). Therefore, the use of such technology may discourage depredating odontocetes, thus avoiding this situation.

This study also confirmed that odontocetes are not the only taxon depredating longlines, with sharks contributing substantially to the economic burden. Large pelagic sharks contributed almost twice as many and caused a similar depredation pattern by removing whole sections of the fish, while cookie-cutter sharks damaged nearly 12 times as many although caused comparatively minor damage. Shark depredation has been reported elsewhere, although some researchers suggest that little can be done to avoid it (e.g. McNeil *et al.*, 2009). However, the results suggest that sharks may also be deterred by the devices. Pelagic shark and odontocete depredation typically render all damaged fish worthless. Although cookie-cutter shark damage is comparatively superficial and may have minimal economic impact on albacore that are typically sold by weight, the high-end sashimi market to which most yellowfin and bigeye are destined demands fish free of even minor blemishes. Therefore, the broader application of these devices to mitigating depredation by predators more generally should encourage continued development and eventual widespread use.

Odontocete bycatch only on control branchlines

The incidence of odontocete bycatch was also low and occurred on control branchlines, suggesting that the devices secondarily mitigated bycatch by first deterring depredating odontocetes. Interestingly, odontocetes were not observed from the vessel during the fishing events in which bycatch occurred, whereas bycatch was not recorded on the several occasions when they were. This outcome brings into question the premise that observation rates are a reliable proxy for the likelihood of odontocete bycatch, at least for the three species observed. This may not be the case elsewhere or under other circumstances, where the presence of animals around the fishing vessel are associated with increased likelihood of bycatch mortality (Hamer and Goldsworthy, 2006; Hamer *et al.*, 2008). Nonetheless, the rarity of such events highlights the need for ongoing commitment to also assessing the efficacy of the devices in mitigating bycatch.

Although each animal was released alive, all departed with an embedded hook and a substantial proportion of the lower end of the branchline. Their fate remains unknown, although the presence of blood in the water and the fact that they retained an entanglement suggests that their health could be substantially compromised, especially if the hook was embedded in the throat or stomach. The "hooking" of odontocetes in this way is recognized as "serious injury" under to the US Marine Mammal Protection Act, for which there is a combined seasonal limit of 2.5 false killer whales serious injuries and mortalities in the Hawaiian pelagic longline fishery (Bigelow *et al.*, 2012). Although no such limits are specified in Australian or Fijian waters, the US interpretation suggests that the fate of bycaught odontocetes that are subsequently released alive under similar circumstances may still be grim.

As with the level of observed fish depredation, observed odontocete bycatch should be considered a minimum. Some animals are likely to escape with an entanglement during the soak at distance from the vessel, thus will go unobserved (Secchi *et al.*, 2005; Kock *et al.*, 2006; Bigelow *et al.*, 2011; Gilman, 2011). The impact of bycatch on the conservation of odontocete populations in Australian and Fijian waters is unclear, although the potential for underestimation when relying solely on fishery logbook or observer records has been flagged in other fisheries (e.g. Hall *et al.*, 2000; Warden and Murray, 2011; Hamer *et al.*, 2013). The status of most odontocete species is generally poorly understood, although recent advances in population genetics reveal that many small populations are susceptible to decline if individuals become bycaught or killed in fisheries (Fullard *et al.*, 2000; Bilgmann *et al.*, 2007; Baird, 2009; Foote *et al.*, 2011). Additionally, some populations are reputed to have adapted their migration patterns to take advantage of foraging opportunities in fishing gear, as may be the case for killer whales off Tasmania (southeastern Australia) around demersal longline vessels fishing for blue-eye trevalla (*Hyperoglyphe antarctica*; AFMA, 2005). It is also possible that the frequency of fishing activities increases the likelihood of depredation (Hamer and Goldsworthy, 2006; Hamer *et al.*, 2008). Therefore, the vulnerability of odontocete populations and the propensity of individuals to become habituated to depredating from fishing gear and becoming bycaught in it highlights the need to continue development and encourage eventual implementation of depredation deterrent technologies.

Summary and future directions

Recent efforts by researchers and fishers (e.g. Moreno *et al.*, 2008; Rabearisoa *et al.*, 2012) inspired and support the development of the two devices assessed in this study. Both had a generally positive impact on target fish catch rates, possibly because it reduced levels of odontocete depredation (and that of pelagic and cookie-cutter sharks), or because target fish were attracted by them. Odontocete bycatch was rare, although occurred exclusively on unprotected branchlines, suggesting that deterrence may also mitigate the risk of depredating odontocetes becoming bycaught. Despite the reported benefits, some issues emerged. First, an extra crewmember was required to handle the devices during setting and hauling, which is likely cost prohibitive in developed countries where wages are high. Although operational integration improves as crew familiarity increases, permanent or automated device attachment may be necessary to resolve this issue. Second, devices did not always deploy when a fish was caught, resulting in some being unprotected and thus depredated. Although there may still be net benefits from using such technology, further material and design improvements are needed if reliability is to improve. Third, the cost of each device and the overall cost of retrofitting a longline remain unclear, because the developmental costs are currently high and unlikely to reflect the per-unit cost of mass production in the long term. This situation will not change unless extensive uptake occurs.

On balance, these results should encourage voluntary uptake of this or similar technology in tropical pelagic longline fisheries where depredation is an economic issue. Undertaking a quantitative cost-benefit analysis of implementing the technology could be beneficial. Specifically, a suite of possible scenarios including key factors associated with the issue (e.g. the value of target species, the cost of depredation damage, the cost of avoidance, reported efficacy level of the technology to be implemented, etc.) would enable fishers to contextualise their problem and identify if they should respond and the limit of investment they should commit. A similar quantitative approach was recently explored for an Alaskan demersal longline fishery with informative results (Peterson *et al.*, 2014).

Voluntary uptake is essential to the success of depredation and bycatch mitigation technologies, especially in longline fisheries where illegal, unregulated, and unreported (IUU) fishing activity is a concerning issue (FAO, 2001). Researchers, managers, and manufacturers have a key role to play in optimizing efficacy, affordability, and integration of similar technologies into affected fisheries. Without this, mandating the use of costly or ineffective technologies will have little influence in IUU fisheries and will require typically costly compliance and monitoring activities in regulated fisheries (e.g. Nielsen and Mathiesen, 2003; Le Quesne, 2009; Kirby and Ward, 2014). Achieving this outcome could improve the economic situation for affected pelagic longline fisheries and the conservation situation for affected odontocete populations; a win–win for both.

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