Physical and psychological deterrence strategies to mitigate odontocete by-catch and depredation in pelagic longline fisheries: progress report

Progress report to Pacific Islands Forum Fisheries Agency (FFA),
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CONTENTS

ABSTRACT

Odontocete by-catch and depredation in pelagic longline fisheries is globally widespread and may have negative impacts on the conservation and welfare of the odontocetes involved and on the economic viability of the fisheries involved. This study attempted to develop two differently designed devices that would prevent odontocetes from depredating caught fish, thus putting themselves at risk of becoming by-caught when doing so. This was achieved using physical deterrence (i.e. by shrouding the fish with a barrier) and psychological deterrence (i.e. utilising prior negative experiences of temporary entanglement in fishing gear) strategies. Both devices were designed to fit directly to a branchline some distance from the hook, then descent towards and shroud the caught fish using a line tension trigger mechanism. Contrary to expectations, incidences of by-catch and depredation were frustratingly rare during the sea trials, suggesting their occurrence varies in time and space. All incidences occurred on control branchlines that were not fitted with a deterrent device, suggesting the potential of this technology to deter depredating odontocetes should not be discounted. The presence of the devices on branchlines had negligible effect on fish catch rates, size and survival, were physically robust and relatively easy to integrate into fishing operations. Although this study provides interesting insights into the development and impact of this technology, a considerably larger data set that more thoroughly and accurately depicts the efficacy of these devices is needed. Future development should also focus on minimising the cost of implementation, in order to ensure voluntary and widespread uptake.

Key words: Operational interactions, odontocete, toothed whale, longline, fishing, depredation, by-catch mortality, deterrence, physical, psychological, acoustic.

Front cover photo credits: Hooked false killer whale (US National Marine Fisheries Service); Depredated albacore tuna (Derek J. Hamer).

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1. INTRODUCTION

As the human population increases globally, so too does the demand for food (Gilland, 2002). Terrestrial food production has struggled to keep pace and has prompted increased interest in offshore fish stocks over the last 4-5 decades as a means of meeting overall food demand, with widespread exploitation by major industrial fisheries now commonplace in all major oceans (Pauly et al., 2005; FAO, 2009). Marine mammals, including odontocetes (i.e. toothed whales, dolphins and porpoises), are also significant consumers in the marine environment, thus resulting in inevitable and extensive geographic overlap with fishing activities and gear, with operational interactions being the inevitable result (e.g. Beverton, 1985; Northridge and Hofman, 1999; Culik, 2004; Read, 2005; Gilman et al., 2006; Hamer et al., 2008, 2011, 2012). In the context of marine mammals and industrial fisheries, and for the purposes of this study, these events include (i) depredation, where fishery catch is removed or damaged by a marine mammal (Read, 2005; Gilman et al., 2006; Hamer et al., 2012), and (ii) by-catch, where depredating marine mammals are caught incidentally (Read et al., 2006; Hamer et al., 2008) or intentionally (Gosliner, 1999).

Depredation by odontocetes from pelagic longlines has become an increasing economic problem in recent decades and is associated with expanding fishing effort in shelf (i.e. artisanal and semi-industrial, typically in coastal, exclusive economic zone [EEZ] waters) and oceanic (i.e. industrial, typically in deep, international waters) environments throughout tropical and temperate latitudes (Gilman et al., 2006; IOTC, 2007; Ramos-Cartelle and Mejuto, 2008; Hamer et al., 2012). These fisheries predominantly target tuna species, although several other scalefish species (e.g barracuda *Sphyraena* spp. and wahoo *Acanthocybium solandri*) may also be commercially important, particularly in the local markets of developing countries. Existing reports from longline fisheries suggest false killer whales *Pseudorca delphis* and pilot whales *Globicephalu* spp. are predominantly involved, although up to 20 species, including killer whales *Orcinus orca*, melon headed whales *Peponocephala electra* and sperm whales

Physeter macrocephalus, also depredate from pelagic longlines (Hamer et al., 2012). Depredating odontocetes often damage caught fish, resulting in recordable economic losses of 20% to 100% each set, or US$1,034 to $8,495 each day, according to anecdotal reports and observed sets (Roche et al., 2007; Tixier et al., 2010; Hamer et al., 2012). However, the economic problem is likely to be understated, because an undetermined number of caught fish are likely to be completely removed and because the presence of odontocetes in the vicinity of baited hooks may deter free swimming fish from approaching baited hooks, although neither can be reflected in catch records (Hamer et al., 2012).

Many odontocete individuals and populations benefit from depredating from fishing gear, including pelagic longlines. Less energy is expended to depredate fish caught on fishing gear compared with pursuits of evasive, free swimming prey, while more energy may be gained by depredating species of caught fish that may otherwise be too large, too fast or occur too deep to catch using natural foraging strategies (Soto et al., 2008; Aoki et al., 2012; Hamer et al., 2012). However, whether depredating individuals are habituated (i.e. deliberately target fishing activities in the knowledge they can obtain caught fish) or naïve (i.e. are not aware of those advantages) to fishing activities, they are at risk of ingesting a hook that may become lodged in their mouth, throat or stomach (Secchi et al., 2005; Hamer et al., 2012). These individuals may drown immediately if they are unable to reach the surface to breath, or may succumb later from associated injuries, infections and starvation (Best et al., 2001; Hamer et al., 2012).

Odontocetes, like most marine mammals, take many years to reach sexual maturity and raise few young during their reproductive lifetime (Leatherwood et al., 1983, Culik, 2004, Wade, 2002; Miller, 2007). On this basis, many odontocete populations are likely to be susceptible to decline, even with the loss of small numbers of individuals from unnatural sources, such as by-catch. Although it remains difficult to confirm a direct link, a number of recent studies have indicated that by-catch in a Hawaiian pelagic longline fishery may have attributed to declines in populations of pilot whales (Waring et al. 2006, Garrison 2007) and false killer whales (Forney and Kobayashi, 2007, Reeves et al., 2009). The impact of by-catch on odontocete populations may be underestimated, because advances in population genetics are beginning to identify smaller, fragmented population 'units' that are inevitably more susceptible to decline under low levels of loss (Fullard et al., 2000; Bilgmann et al., 2007; Foote et al., 2011). The full extent of the by-catch problem may be masked by a widespread lack of compliance to fishery management conditions that include mitigation and reporting requirements, thus making it difficult to calculate estimates (FAO, 2001; Lukoschek et al., 2009).

To date, strategies to mitigate by-catch and depredation of odontocetes on pelagic longlines have primarily focused on the development and implementation of acoustic technologies (Jefferson and Curry, 1996). These can broadly be separated into four groups: acoustic harassment devices (AHDs; Nowacek et al., 2007), acoustic deterrent devices (ADDs; Dawson et al., 1998), echolocation disruption devices (EDDs, Mooney et al., 2009) and passive listening arrays (PLAs; McPherson et al., 2008). However, there are a range of issues associated with these technologies that have impeded their success and implementation. For example, AHDs are marred by ethical concerns relating to the welfare of the target species and the impact on the broader marine ecosystem (Morton and Symonds, 2002), while ADDs and EDDs may eventually become attractants (i.e. 'the diner bell effect') when the marine mammal species it is intended to deter becomes accustomed to its presence (Jefferson and Curry, 1996; Mooney et al, 2009) and PLAs may be impractical in situations where the fishing gear is set over large distances (McPherson et al., 2008).

Although having received comparatively little attention previously, physical mitigation technologies may be a practical alternative. Physical deterrence was first explored to mitigate sperm whale depredation from demersal longlines in the Chilean Patagonian toothfish *Dissostichus eleginoides* fishery (Moreno et al., 2008). Although sperm whales are known to consume benthic prey in some locations (Best, 1999), depredation was thought to occur during the haul, at the end of the set, as the gear ascended through the pelagic zone to the vessel. A device known as the 'net sleeve', comprising a large and rigid cage, was developed to combat this problem (Moreno et al., 2008). The net sleeve would descend the branchline during the haul, under the influence of gravity and drag, eventually shrouding the caught fish. The resulting physical protection led to an 83% reduction in depredation (Moreno et al., 2008).

In contrast, pelagic longlines are set in the upper water column in waters 30-300 m deep (Bjordal and Lokkeborg, 1996), where most small odontocete species concentrate their natural foraging effort (e.g. Baird et al., 2002; Soto et al., 2008). This suggests pelagic longlines are exposed to being depredated throughout the entire fishing event (sometimes referred to as the 'soak'), thus devices designed to mitigate odontocete by-catch and depredation must be necessarily and comparatively complex to combat the problem. Specifically, the baited hook must be able to fish unimpeded *before* a fish is caught, then 'trigger' the deployment of a deterrent device and structure *after* a fish is caught to protect the fish until it is hauled aboard the vessel. Anecdotal reports of caught fish remaining undamaged in or near tangles in pelagic longline gear suggest that depredating odontocetes may be deterred, either because they are unable to gain access to the fish within the tangle (i.e. physical deterrence; Hamer et al., 2012), or because they are fearful of becoming caught in the tangles (i.e. psychological deterrence; Kock et al., 2006).

In 2009, the Australian Marine Mammal Centre (AMMC) [1] commenced the development of two devices based on these two principals, which have become known as the 'chain device' (a pod containing two small-link stainless steel chains of 1500 mm length each, which hang beside the caught fish when triggered) and as the 'cage device' (a cage made of monofilament fishing line 450 mm in diameter and 850 mm in length, which envelopes the caught fish when triggered; Hamer et al., 2012). The objective was to produce an unobtrusive addition to the existing fishing gear that would directly attach to each

[1] The AMMC is part of the Australian Government Environment Department (DSEWPaC), with core business focusing on non-lethal methods of studying whales and on applied research aimed at mitigating the general impact of human activities on marine mammals.

branchline well clear of the baited hook, remaining there until the tension of a caught fish triggered the device, causing it to (i) descend toward the caught fish under the influence of gravity and (ii) release the simulated tangle structure to shroud the fish (Figure 1). It was hoped that the structure would deter depredating odontocetes, either physically or psychologically, thus mitigating the incidence of depredation and associated by-catch.

1.1 Aims of this study

There are significant conservation and commercial benefits in mitigating odontocete by-catch and depredation events in longline fisheries, which underpin the commissioning of this study. Generally, the aim was to test the efficacy (i.e. prove the concept) of the two devices as a physical or psychological deterrent to depredating odontocetes. Specifically, the aims were to determine the effect of the devices on rates of (i) odontocete by-catch, (ii) odontocete depredation and (iii) target fish catch. Other aspects of the fishing operation were also of interest, including (i) device sink rate, (ii) target catch survival, (iii) target catch size distribution and (iv) operational integration of the device. It is hoped that the outcomes of this study will offer the first tangible step towards finding a partial or complete solution to this complex problem and that it may be transferable to other pelagic longline fisheries worldwide, regardless of the depredating odontocete species, gear configuration, or target fish species.

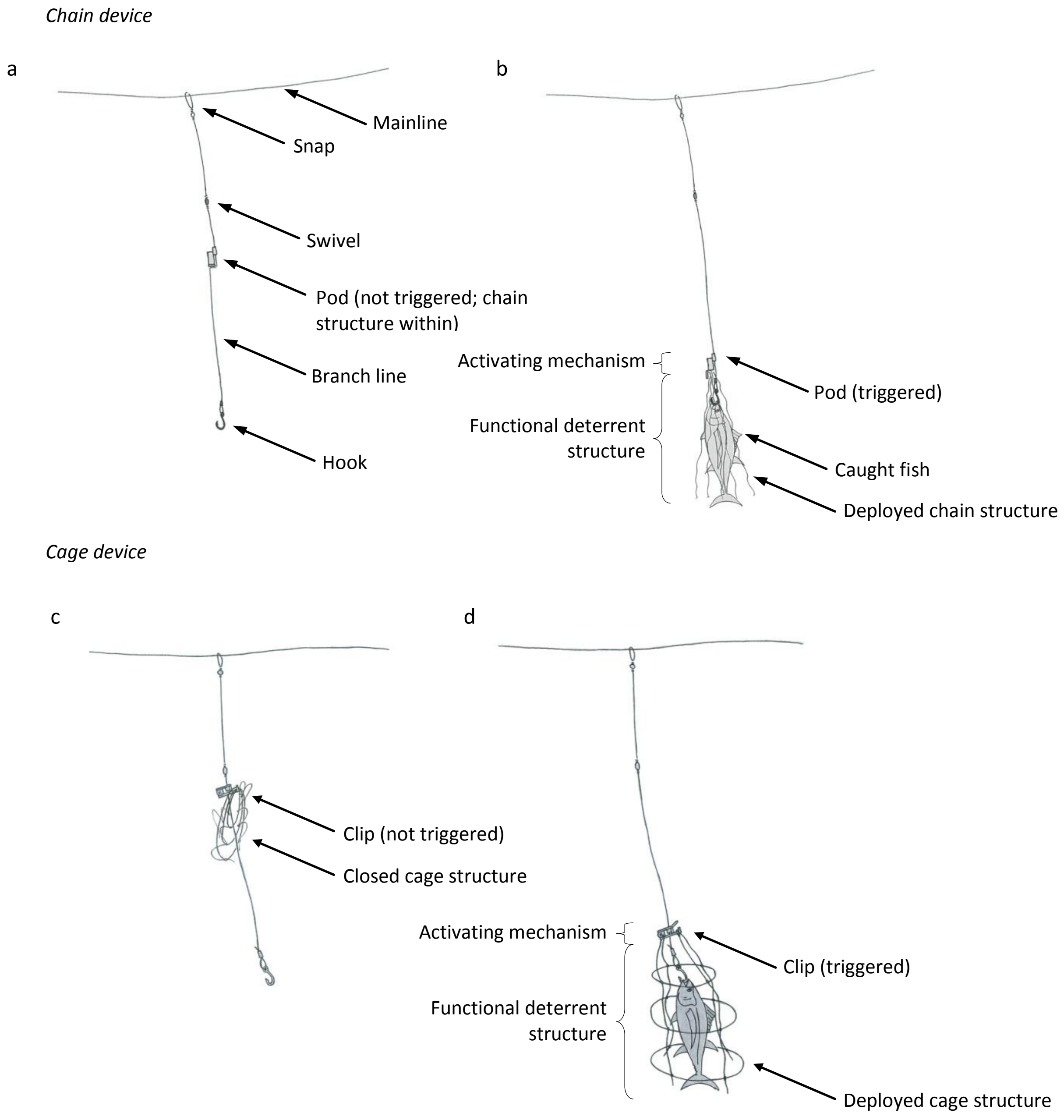


Figure 1 Schematic diagram of the *chain device* and *cage device* (a,c: not triggered; b,d: triggered) currently under development by the Australian Marine Mammal Centre. Both devices are designed to physically and/or psychologically deter depredating odontocetes, thus mitigating the incidence of odontocete depredation and by-catch. Before the devices are triggered by the tension of a caught fish, they remain clear of the baited hook, closer to the mainline. Upon being triggered, the activating mechanism causes the device to descend toward the caught fish using gravity and/or drag, and release the functional deterrent structure (modified from Hamer et al., 2012).

2. METHODS

2.1 Exploratory voyage: characteristics of fishing

As a means of guiding the development of mitigation devices, the characteristics of a ‘normal’ fishing operation were observed and described. During December 2009, an observer (DJH) accompanied the 24 m Australian registered longlining fishing vessel *FV Fortuna 2* during fishing in the Coral Sea, in the northeast of Australia’s EEZ. At the beginning of each fishing event, the observer recorded (i) location, (ii) time of day, (iii) duration of setting, (iv) bait type and (v) the number and species of free-swimming odontocetes around the vessel. During hauling, the observer recorded (i) time of day, (ii) number and species of caught fish, (iii) nature of any damage sustained, (iv) the number, species and nature of by-caught odontocetes, (v) the number and species of free-swimming odontocetes around the vessel and the (vi) descriptions of gear tangles. Other information was collected relating specifically to the fishing operation. All of the information collected was used to inform development and design of the devices prior to manufacture and appropriate ways to assess their performance.

2.2 Device design and development

Based on the information obtained on the *FV Fortuna 2*, the cage device and chain device were subsequently developed, representing two different approaches to deterring depredating odontocetes using simulated fishing gear tangles. Each device contained an (i) functional deterrent structure and (ii) activating mechanism (Figure 1). For the cage device, the functional deterrent structure was comprised of a cage manufactured from fishing gear readily available on the vessel (i.e. nylon monofilament 1.9 mm diameter branchline and 3.1 mm diameter main line, plus aluminium swages [crimps] to join the components together). Three rings of main line of 450 mm diameter were joined together by four strands of branchline to produce a 900 mm long tube-like structure. Although prescribed for this study to ensure comparability during experimental sea trials, the cage could be altered to suit the dimensions of the fish species targeted. For the chain device, the functional deterrent structure was comprised of two lengths of 2 mm thick stainless steel chain with a link size of 7mm by 16 mm. Again, the chain specifications were prescribed for the study, but could be easily substituted with lighter or shorter chain, or another material.

The activating mechanism of both devices (i.e. the ‘clip’ for the cage structure and the ‘pod’ for the chain structure) both contained two features that set them apart from the comparatively rigid and primitive net sleeve used in the Patagonian toothfish demersal longline fishery (Moreno et al., 2008). Firstly, a tension sensitive release system was included to release the functional deterrent structure (i.e. the cage or the chain) from the activating mechanism when a fish became caught on the baited hook. This functioned by first holding the device in a *closed* state, well clear of the hook before a fish was caught, by routing the branchline through a ‘dog-leg’ or direction change on the containment cap (Figure 1a and c). Once a fish was caught, the tension exerted by the resisting caught fish would force the branchline to straighten and the containment cap to *open* or be ‘triggered’, thus releasing the cage or chain structure (Figure 1b and d). Secondly, a one way cam system was included to ensure the triggered device would only travel toward the caught fish. The cam system contained one or two spring-loaded cams that applied ‘pinching’ pressure to branchline when gravity or water drag attempted to move the device away from the caught fish.

The activating mechanisms of the cage device (i.e. the clip) was entirely developed by the AMMC and manufactured by 3D Systems Australia (Hawthorn, Victoria Australia), while the activating mechanism of the chain device (i.e. the pod) was collaboratively designed by the AMMC and Fishtek Limited (Moretonhampstead, Devon, United Kingdom) and manufactured by Fishtek Limited and 3D Systems Australia. The ownership of intellectual property and associated development and production of both devices is vested under licence exclusively to the Australian Government (being recognised as permanent, irrevocable, royalty free and worldwide), which prevents the use, copy, supply or reproduction of any associated materials without prior permission while in the developmental phase. It is the intention of the AMMC to make the technical designs and associated information publically available upon the completion of this developmental study.

2.3 Effect of devices on gear sink rate

The overall weight of the cage device was 40.7 g in seawater and of the chain device was 60.8 g in seawater, with both being sufficiently large to cause considerable hydrodynamic drag when moving. As such, it was though that the combination of weight and drag may alter the sink rate and behaviour of the 'normal' fishing gear. The Australian Maritime College Circulating Water Channel (CWC) facility (Beauty Point, Tasmania, Australia) was used to test the effect of these two factors when the gear is deployed. Although the ground speed of the longline gear during deployment at sea is effectively zero during deployment, the gear will sink as the line descends to the fishing depth of the soak and the forward movement of the (typically 5-7 knots) will cause the marginally elastic mainline to 'spring back'. Both factors may result in some degree of relative horizontal ground speed being applied to the fishing gear. The CWC is the largest of such facilities in Australia (i.e. 17.2 m long, 5 m wide and 2.5 m deep) where horizontal water flow can be controlled (up to 1.5 m/s [2.92 knots] at 0.5 m increments), thus making it possible to simulate the initial stages of a set as the gear sinks to the 'fishing' depth. Three 6 m long branchlines were used for the experiment, with two containing one of the two devices at the half way point (i.e. the 'treatments') and the third without a device (i.e. the 'control'). A 60 g lead sinker was attached at the bottom end of each of the three branchlines as a proxy for a hook baited with a sardine *Sardinops* spp. The top end of each branchline was attached to a stationary observation carriage at 1.5 m above the surface of the water.

To obtain sink rate profiles, a time and depth recorder (TDR; G5 Long Life, CEFAS Technology Limited, Lowestoft, UK), measuring 35 mm in length and 11.5 mm in diameter, and weighing 2.3 g in seawater, was attached adjacent to each device on the treatment branchlines and to the same position on the control branchline. Several previous studies of pelagic longlines have used these TDRs to determine the sink rate of baited hooks when testing seabird by-catch mitigation technologies (e.g. Robertson et al., 2006). However, the purpose of this study was to determine the effect of the devices under development for odontocete depredation and by-catch mitigation. As such, rather than being attached to the hook substituting lead sinkers, TDRs were attached directly to the devices on the two treatment branchlines and to an analogous location on the control branchline.

The TDRs measured depth once per second, allowing the construction of a vertical profile (complete with variance) for visually comparing differences in sink rate between the cage device, chain device and control branchline. Each of the three branchlines was released from the observation carriage simultaneously and then retrieved after coming into contact with the bottom of the tank, with the cycle being repeated until 100 replicates was obtained. This procedure was repeated at three water speeds, being 0 m/s, 0.5 m/s (0.97 knots) and 1 m/s (1.94 knots). A bivariate plot of depth (dependent variable) against time (independent variable) was constructed, depicting the mean depth that each device sunk at each second after coming into contact with the surface of the water.

2.4 Experimental design for sea trials

The sea trials were conducted on the *FV Sarah J* in the Coral Sea during July 2011 and on the *FV Solander 14* and *FV Sea Knight* in the Fijian EEZ during November and December 2011. The longline fishing gear used on all vessels during this study generally conformed to typical gear configuration, although variations in terminology have been standardised for consistency. The overall length of the mainline (backbone) deployed during each fishing event was approximately 78 km (40 nm) long, hanging between buoys (floats) separated by about 700 m, at depths ranging between 35 and 300 m. Between 28 and 35 branchlines hung between each buoy, depending on the setting ratio agreed upon by the Master and the observer. Each branchline was 10 to 12 m long and attached to the mainline by a snap (clip), with a baited hook at the opposite end, sometimes with a swivel (weighted or unweighted) approximately 3 m away from the hook.

For the purpose of the sea trials, the gear was divided into two sections; experimental gear and non-experimental gear (Figure 3). The only difference between these two sections was that the devices were present on the experimental gear and were *not* present on the non-experimental gear. The devices were used to facilitate a controlled feeding choice experiment, where it was thought that fish shrouded by a device (the treatment effect) would deter depredating odontocetes, who would then chose unshrouded fish (the control effect) to feed on in preference. Specifically, devices were placed on every second branchline; a cage device (treatment) on one branchline, nothing on the second (control), a chain device on the third (treatment), nothing on the fourth (control), and so on (Figure 3). During each fishing event, this method of setting the gear and devices in the experimental section was repeated until approximately 250 units of each device were deployed, totalling 500 devices and 1000 treatment and control branchlines. As it was not known if the proximity or presence of a device had an effect on an adjacent control branchline on the experimental gear (i.e. the boundary effect), a non-experimental section of mainline of comparable size (i.e. containing another 500 branchlines) was also set that did not contain any devices, instead being, in effect, a continuous series of control branchlines. To quantitatively test for the presence of a boundary effect, fish catch rates were calculated and compared for the control branchlines in each of the two sections.

2.5 Data collection and analysis

In summary, sea trials were conducted to assess the efficacy of the two depredation mitigation devices being developed in (i) reducing odontocete by-catch and (ii) catch depredation, without (iii) reducing catch rate. The same observer (DJH) was used throughout the trial and accompanied pelagic longline vessels on three occasions between July and December 2011; once in Australian waters (*FV Sarah J*) and twice in Fijian waters (*FV Solander 14* and *FV Sea Knight*). In a similar manner to the December 2009 trip on *FV Fortuna 2*, during setting the observer recorded (i) location, (ii) time of day, (iii) duration of setting, (iv) bait type and (v) the number and species of free-swimming odontocetes around the vessel. Observations during hauling were more involved, with the records including (i) time of day, (ii) the presence or absence and (iii) species of caught fish, (iv) the nature of damage that caught fish sustained and (v) by what (i.e. odontocetes, cookie cutter sharks *Isistius brasiliensis* or other sharks [Chondrichthyes]), (vi) the length (i.e. from upper mandible to fork of tail) and (vii) survival (i.e. deemed alive if either regular body or gill movement was detected) of caught fish, (viii) the presence, species and age of by-caught odontocetes (it was expected that it would not be possible to determine the gender of most odontocete species) and (ix) the nature of damage they had sustained (i.e. hooked in the mouth or externally, plus other visible signs of injury), and (x) the number and species of free-swimming odontocetes around the vessel. A regional map was produced to highlight the approximate location of all fishing events, including those during the initial trip in 2009 and those during the experimental sea trials in 2011. Rates of fish catch and depredation were plotted as histograms for treatment and control branchlines in the experimental section and for control branchlines in the non-experimental section. All calculated means were presented with standard error (SE).

Operational integration of the depredation mitigation devices was determined by calculating the time that elapsed (as minutes), from the beginning to end of setting and from the beginning to end of hauling the experimental and non-experimental gear. Other qualitative observations were made, including (i) how many additional crewmembers were needed during the set and haul, (ii) how frequently the devices were damaged or caused gear damage and (iii) the difficulties most often encountered by crewmembers when handling the devices.

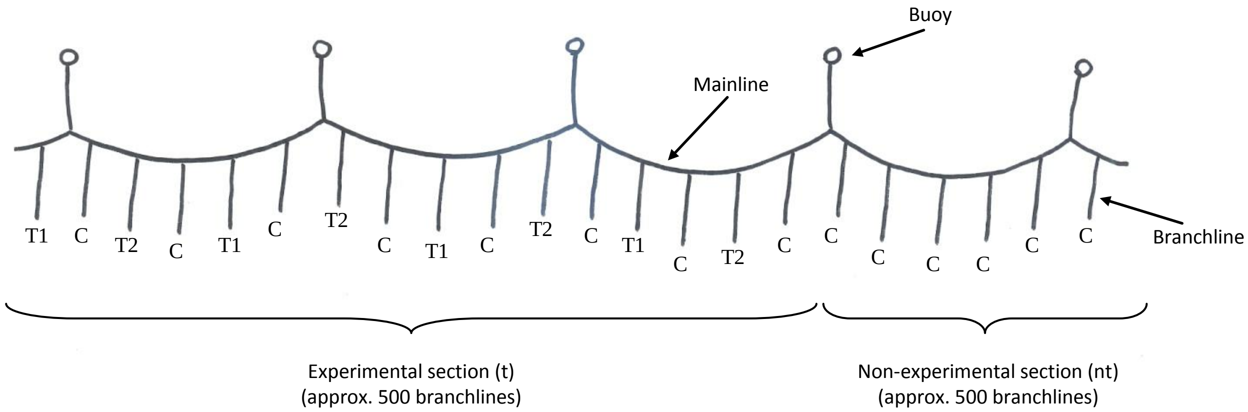


Figure 2 Schematic diagram, not to scale, of pelagic longline configuration used during sea trials, depicting the treatment (Cage device ['T1'] and Chain device ['T2']) and control ('c') in the experimental section ('t') and the control branchlines ('c') in the non-experimental section ('nt'). The control branchlines in the experimental section were the same as the control branchlines in the non-experimental section.

3. RESULTS

3.1 Characteristics of fishing operation

During December 2009, the observer monitored 13 fishing events, amounting to 27,830 hooks (number of fishing events = 13; mean number of hooks per fishing event = 2141 ± 384). Hooks were baited with either sardine or squid (typically *Loligo* spp.). There were 587 fish caught in total, comprised 10 species of commercial value and equating to 0.021 fish per hook, or one fish every 47 hooks on average (Table 1).

Fish exhibiting odontocete depredation were observed during three (23.1%) of these fishing events, affecting 53 of the fish landed, or 9% of the commercially valuable catch. Three fish species were involved, being albacore tuna *Thunnus alalunga*, yellowfin tuna *Thunnus albacares* and mahi mahi *Coryphaenidae hippurus*. The damage resulted in either the complete removal of the torso behind the gill plates and gills, or deep and numerous lacerations on the torso, being consistent with odontocete depredation damage reported previously and distinct from damage caused by pelagic sharks (see Hamer et al., 2012). Interestingly, odontocetes were not observed in the vicinity of the vessel at any time, before, during or after these three fishing events.

Three individual odontocetes were observed by-caught during two fishing events, at a rate of 1.08×10^{-4} (i.e. 0.000108) individuals per hook, or one individual every 9,276 hooks on average (Table 1). All three were confirmed to be false killer whales of adult size, with each being hauled to within approximately 10 m of the vessel and then released alive by cutting away the branchline. All appeared to be hooked either in the lip or mouth (see Figure 3 in Hamer et al., 2012). Their subsequent fate remains unknown, although due to large size of the by-caught individuals, the risk of injury to crewmembers was deemed too great to haul the individuals closer to the vessel to affect a more thorough release and disentanglement from the fishing gear. No other odontocetes were observed before, during, or after those by-catch events. A small number of individuals were observed during the haul of one other fishing event and were thought to be short finned pilot whales (*Globicephala melas*), although no depredated fish were observed when the gear was hauled.

During fishing events, setting typically commenced at 0530 to 0730 and hauling commenced at 1630 to 1830. Mean setting duration was 234 ± 11 minutes (3.9 ± 0.18 hours) and mean hauling duration was 749 ± 85 minutes (12.48 ± 1.42 hours), while the mean time elapsed between hooks was 6.56 ± 1.48 seconds and 20.99 ± 12.70 seconds, respectively (Table 2). Hypothetically, based on these figures, if attaching and removing devices resulted in an increase of one second between hooks during the set and the haul, then it is predicted that fishing activities would increase by 286.6 minutes (4.8 hours), or by 29.2%.

3.2 Gear sink rate

The gear configuration used in this study was consistent with that most commonly used throughout the pelagic longline industry. It was found that the control gear achieved depths of 1.8 to 2 m after 2 seconds, whereas it took 3 to 4 seconds (up to twice as long) for the Chain device to reach similar depths and 5 to 6 seconds (up to three times as long) for the Cage device to reach similar depths (Table 3; Figure 4). In general, the presence of the devices and increased horizontal water speed slowed the descent of the branchline. Nonetheless, the presence of the devices did not appear to affect the behaviour of the branchline, which sank in the same manner as the control branchline on every occasion, without exhibiting and detectable oscillation of rotation.

3.3 Results of sea trials

3.3.1 Fish yield

Due to similarities in gear configuration, fishing method, catch composition and rates of odontocete depredation and by-catch, the data collected in Australian and Fijian EEZs was combined. A total of 23 fishing events were conducted during the sea trials, amounting to 20,257 hooks (mean number of hooks per fishing event = 876 ± 532) observed hauled (Figure 5). All hooks were baited with sardine. Of the total 971 fish caught, there were 13 species of commercial value, equating to a rate of 0.048 fish per hook, or one fish every 21 hooks on average (Table 1). In the experimental section, the treatment branchlines performed slightly better than the control branchlines; catch rates for the Cage device and Chain device were 0.058 and 0.057 fish per hook (18 and 17 hooks per fish) respectively, while the catch rate for the control branchlines was 0.049 fish per hook (21 hooks per fish; Table 1; Figure 5). Additionally, the control branchlines in the experimental section performed slightly better that the controls comprising the non-experimental section, the latter catch rate being 0.036 fish per hook (29 hooks per fish).

3.3.2 Odontocete depredation

During the sea trials, odontocete depredation only occurred on branchlines without devices attached (Table 1; Figure 5). There were four fish observed depredated during only one fishing event, again being albacore tuna, yellofin tuna and mahi mahi. Three occurred on control branchlines in the experimental section and one occurred in the non-experimental section. Each was near complete, with extensive and deep tooth lacerations to the torso. Odontocetes were not observed before, during or after this fishing event. Overall, depredation amounted to 0.5% of the catch recorded during the sea trials by number, or 80% of the catch during the set when depredation occurred (i.e. four of the five fish caught).

Interestingly, 106 fish (10.9% of the catch) were depredated by cookie cutter sharks, being much higher than depredation by odontocetes and with 101 (95.3%) of those occurring on control gear (Figure 5). Other pelagic sharks depredated 10 fish (1% of the catch), with nine (90%) occurring on control gear (Figure 8). Bait depredation was recorded during five fishing events, although it was not possible to attribute it to depredating odontocetes, because some aspects of the damage suggested small pelagic fishes or squids may have been involved.

3.3.3 Odontocete by-catch

One odontocete was observed by-caught in the Fijian EEZ, on a control branchline in the experimental section of the gear (Table 1). Based on colour patterns and overall body shape, the individual was confirmed to be a melon headed whale *Peponocephala electra*. For the Australian and Fijian sea trials combined, this equated to a by-catch rate of 1.37×10^{-4} (i.e. 0.000137) individuals per hook, or one individual by-caught every 7,213 hooks (Table 1). Odontocete by-catch rates for treatment (i.e. Cage device and Chain device) and control branchlines in the experimental gear, and for experimental and non-experimental sections overall are also provided (Table 1).

In a manner similar to the initial trip in 2009, the individual was hauled to within approximately 10 m of the vessel and then released by cutting away the branchline. The individual was caught in either the lip or mouth, wile a considerable volume of blood was observed in the water around the head of the individual. No other odontocetes were observed by-caught or free swimming close to the vessel during the remainder of the sea trials.

3.4 Impact of devices on fishing operation

3.4.1 Size and survival of caught fish

Fish size on experimental and non-experimental gear was recorded for the two trips in the Fiji EEZ (Figure 6). The sale value of yellowfin and bigeye tunas increases disproportionately with size, thus it was deemed important to measure the effect of the devices on this parameter. The seven most abundant fish caught, in order of quantity landed on the deck, were albacore, lancetfish *Alepisaurus* spp., yellowfin, mahi mahi, barracuda, wahoo and bigeye *Thunnus obesus*. Lancetfish were not retained because they had no commercial value, thus will not be considered further here. Visual inspection of the results indicate that size varied negligibly in albacore, mahi mahi, wahoo and barracuda, between treatment and control branchlines in the experimental gear and between experimental and non-experimental sections. However, the average size of yellowfin and bigeye was larger in the non-experimental section (Figure 6).

Fish survival was also recorded for experimental and non-experimental gear deployed during the two trips in the Fiji EEZ (Figure 7). The sale price of the more valuable target species, such as yellowfin and bigeye tunas, can increase markedly if fish are landed alive on the vessel, thus it was deemed important to measure this parameter. Visual inspection of the results indicated that the six commercially valuable fish were affected by the presence of the devices in different ways. For example, survival was lowest on the control branchlines in the experimental section for albacore (8.8%) and bigeye (50%) and mahi mahi (42.1%), while survival was lowest in the treatment branchlines of the experimental section for wahoo (0%) and lowest in the non-experimental section for yellowfin (33.3%). In general though, survival was low for albacore (8.8 to 38.8%) and wahoo (0 to 22.2%) when compared with the other species.

3.4.2 Setting and hauling times, and device durability

The setting speed was slower during the sea trials when devices were being deployed, compared with during the exploratory trip where devices were not used. Specifically, setting was over 2 seconds slower per hook during the sea trials than during the exploratory trip (Table 2). However, this was due to the setting strategy being predetermined by the Master (whereby the speed of the vessel and the line setter machine on the stern of the vessel are set), rather than by the pace at which crewmembers can deploy the devices. Nonetheless, during the sea trials, an extra crewmember was needed during setting to prepare the devices for attachment to the longline gear.

Each of the approximately 250 units of both designs was deployed during each of the 23 fishing events. Very little effort was required to maintain their functionality. Specifically, there were no recorded structural failures of activating mechanisms of either design, un-triggered or triggered. During two of the earlier sets, several devices of both designs were found to have slipped down the branchline and had become positioned in close proximity to the baited hook. This was easily rectified during trials with minor adjustments to the one way cam system. On rare occasions, after a fish was caught on a cage device (Figure 8), there was a need to realign the deterrent structure. Although this required the attention of one crewmember, the adjustments were simple and swiftly actioned, without impeding the gear hauling process. Between one and three devices became extensively tangled during each haul, always in association with a caught fish. These were also dealt with swiftly, at the end of the fishing event. Perhaps most importantly, there were almost no occasions of devices triggering in the absence of a caught fish, or devices not triggering when a fish was caught. Occasions when either of these circumstances occurred were always associated with gear tangles that prevented the proper function of the device.

Prior to commencing the sea trials, one Master voiced concern about the weight of the devices and the effect it may have on how deep the gear may sink to during the soak. However, it became apparent after a number of fishing events had been conducted that fish catch and composition were similar to expectations, thus suggesting the gear was sinking to a similar depth to that expected without the devices attached. All of these outcomes are favourable, suggesting that only minimal adjustments to normal setting practices need to be made to accommodate the devices.

Table 1 Summary of fishing effort, fish catch, catch depredation and odontocete by-catch across experimental gear (treatment branchlines with either the *Cage Device* or *Chain Device* attached, or control branchlines with no device attached) and non-experimental gear (all control branchlines with no device attached). Collected during pelagic longline sea trials in the Australian and Fijian EEZs to determine the effect of developmental *Cage device* and *Chain device* on odontocete depredation and by-catch on pelagic longlines.

OBSERVED FISHERY AND ODONTOCETE ACTIVITY	EXPLORATORY	SEA TRIALS			
		Experiment			Non – exp.
		Treatment		Control	
	(all controls)	Cage device	Chain device		(all controls)
• *Fishing effort*					
# of sets	13	23	23	23	11
# of hooks	27,830	3,786	3,392	7,213	5,772
• *Fish catch (observed)*					
# caught	587	221	192	358	200
Rate (fish per hook)	0.021	0.058	0.057	0.049	0.035
Rate (hooks per fish)	47	18	17	21	29
• *Catch depredation (observed)*					
# of fish	53	0	0	4	1
% of fish caught	9			1.1	0.5
# of sets involved	3			1	1
% of sets involved	23.1			4.4	9.1
• *Odontocete by-catch (observed)*					
# of individuals	3	0	0	1	0
Rate (odontocetes per hook)	1.08×10^{-4}			1.37×10^{-4}	
Rate (hooks per odontocete)	9,276			7,213	
# of sets involved	2			1	
% of sets involved	15.4			4.4	

Table 2 Summary of setting and hauling speed (in decimal minutes, with SE) during fishing events across experimental gear (treatment branchlines with *Cage Device* or *Chain Device* attached, or control branchlines with no device attached) and non-experimental gear (all control branchlines with no device attached). Collected during and exploratory voyage and sea trials on pelagic longliners in the Australian and Fijian EEZs, to determine the effect of developmental *Cage device* and *Chain device* on odontocete depredation and by-catch on pelagic longlines.

FISHING ACTIVITY	EXPLORATORY	SEA TRIALS	
		Experiment	Non – exp.
	(all controls)	treat. & cont.†	(all controls)
• *Fishing effort*			
# of sets	13	13	11
# of hooks	27,830	9,937	5,772
Mean hooks per set	2,141 ± 384	764 ± 56	525 ± 124
• *Duration (minutes)*			
Set	234 ± 11	172 ± 24 ††	
Haul	749 ± 85	265 ± 62	191 ± 52
• *Processing speed (seconds)*			
Set	6.6 ± 1.5	8.6 ± 1.1	
Haul	21 ± 12.7	20.8 ± 4.8	21.8 ± 6.6

† Data in the experimental section for both treatment and control gear were combined, because it was difficult to separate processing time between each branchline.

†† Setting data for experimental and non-experimental sections of the gear were combined, because setting speed was predetermined and fixed by line setter machine.

Table 3 Summary of branchline sink rates of pelagic longline branchlines with devices attached (the treatment) and without devices attached (the control), in the CWC at the Australian Maritime College (Beauty Point, Tasmania, Australia), for horizontal waters speeds of 0, 0.5 and 1 m/s.

TREATMENT	HORIZONTAL WATER SPEED		
	0 m/s	0.5 m/s	1 m/s
control	1	0.93	0.90
Chain device	0.72	0.69	0.56
Cage device	0.39	0.38	0.37

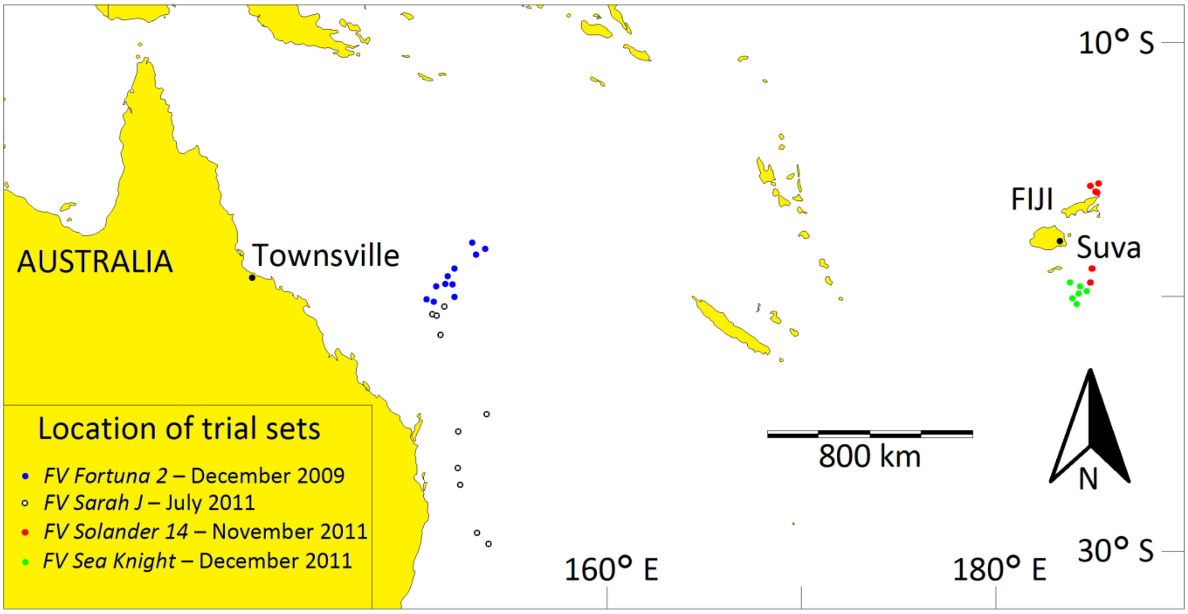


Figure 3 Map of South Pacific region, showing geographic distribution of fishing effort of vessels during pelagic longline sea trials in the Australian and Fijian EEZs to determine the effect of developmental *Cage device* and *Chain device* on odontocete depredation and by-catch on pelagic longlines.

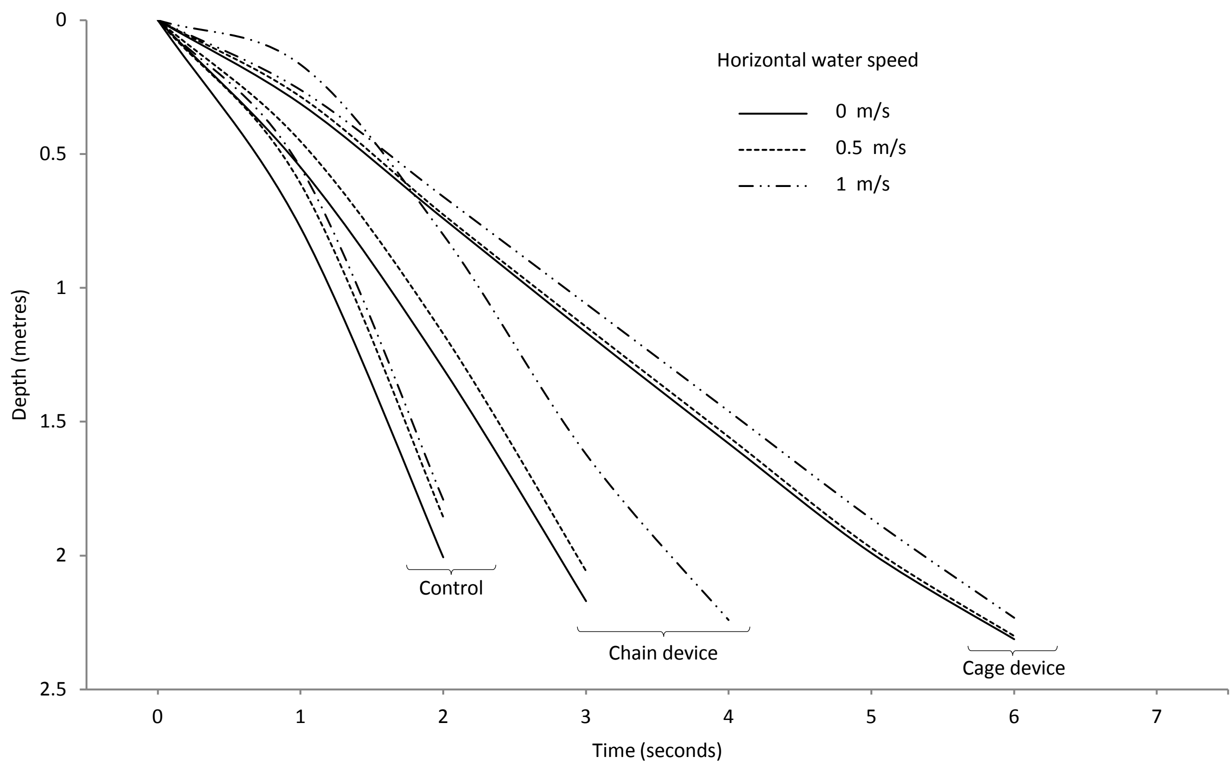


Figure 4 Summary of sink rate experiment in 2.5 m deep CWC, to determine the effect of 'treatment' branchlines (i.e. with a *Cage Device* or *Chain Device* attached) and 'control' branchlines (i.e. without a device attached) on sink rate during setting, at three horizontal waters speeds.

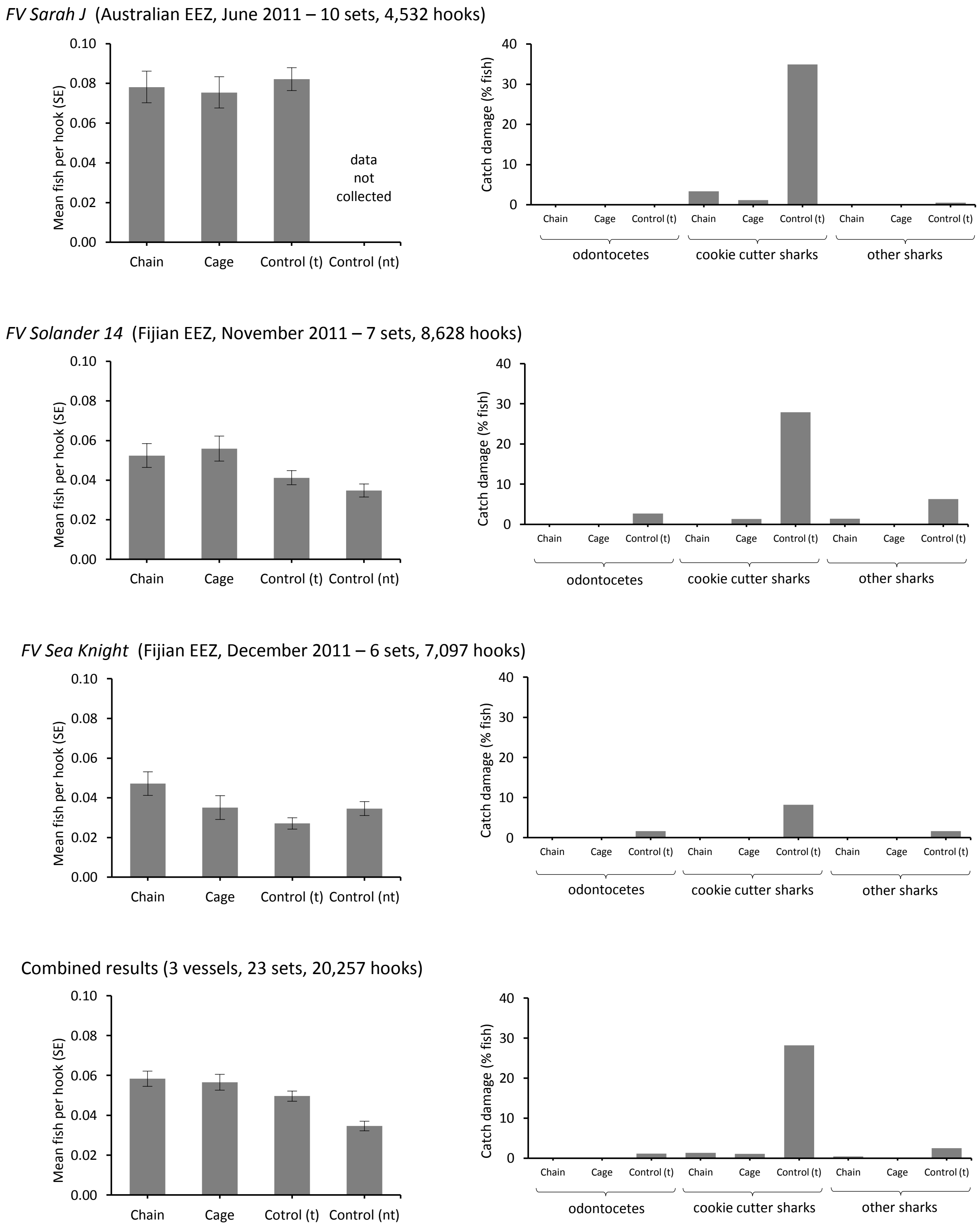
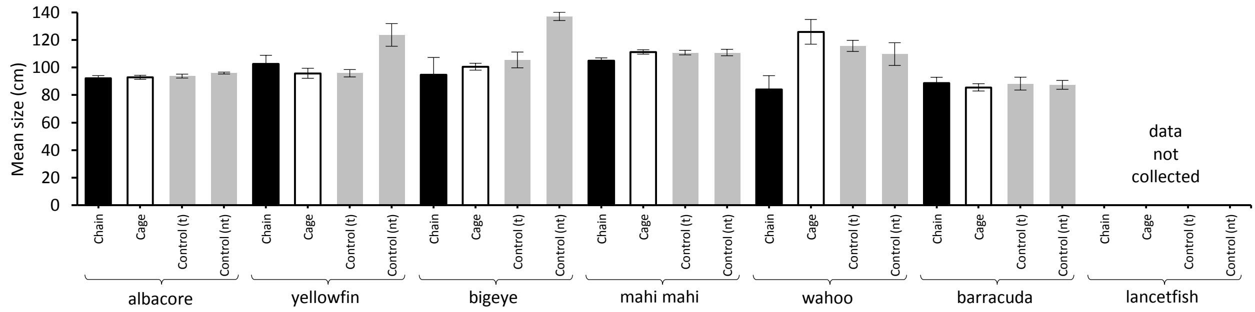


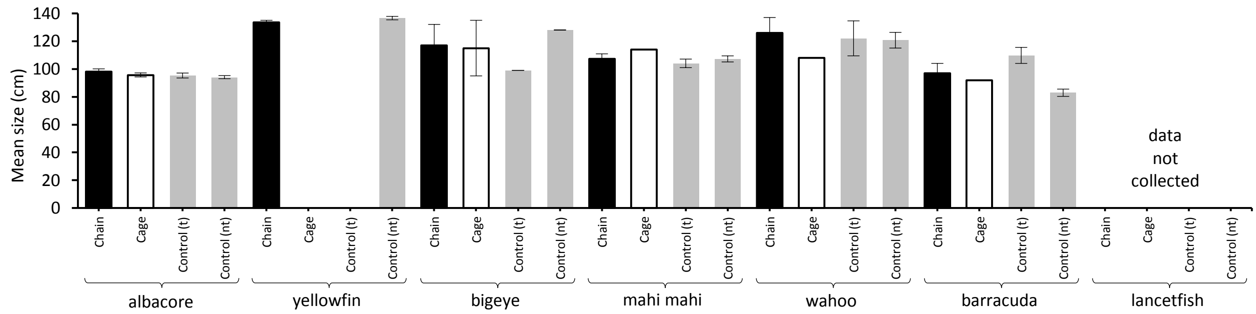
Figure 5 Summary of catch (rates; left column) and depredation damage (percentages; right column) across experimental (t) gear (treatment branchlines with either the *Cage Device* or *Chain Device* attached, or control branchlines with no device attached) and non-experimental (nt) gear (all are control branchlines without devices attached). Collected during pelagic longline sea trials in Australian and Fijian EEZs to determine effect of developmental *Cage device* and *Chain device* on odontocete depredation and by-catch. Presented by vessel and combined.

FV Sarah J (Australian EEZ, June 2011 – data not collected)

FV Solander 14 (Fijian EEZ, November 2011 – 7 sets, 8,628 hooks)



FV Sea Knight (Fijian EEZ, December 2011 – 6 sets, 7,097 hooks)



Combined results (2 vessels, 13 sets, 15,725 hooks)

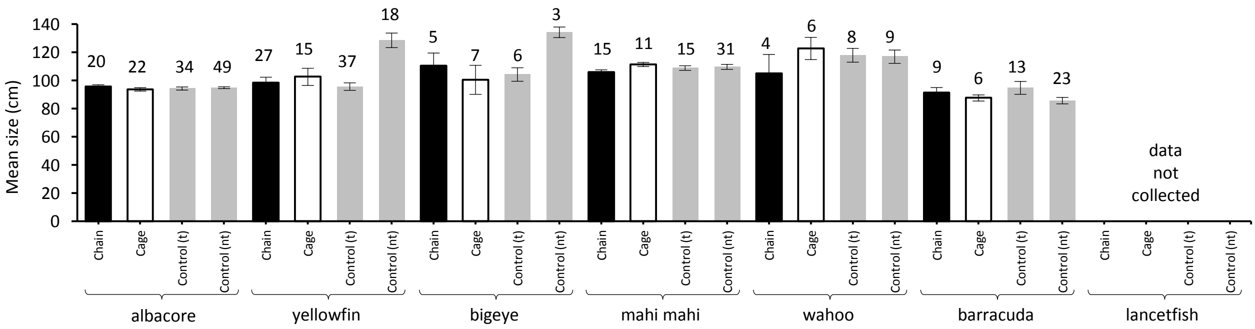
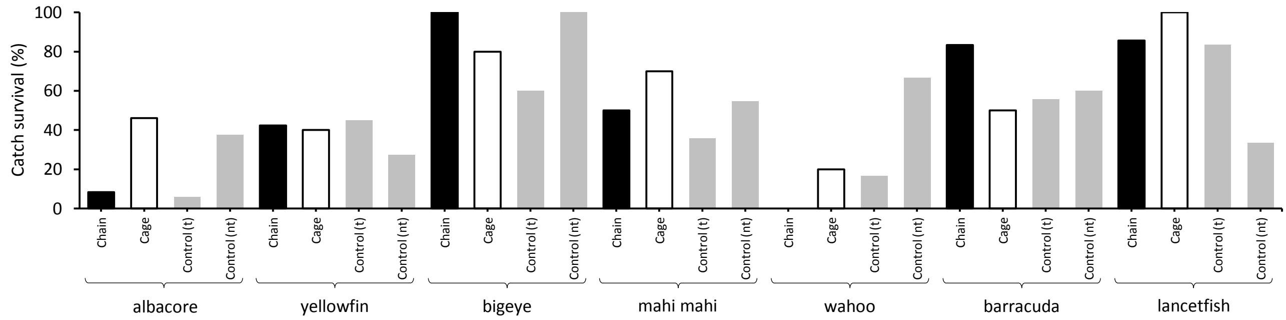


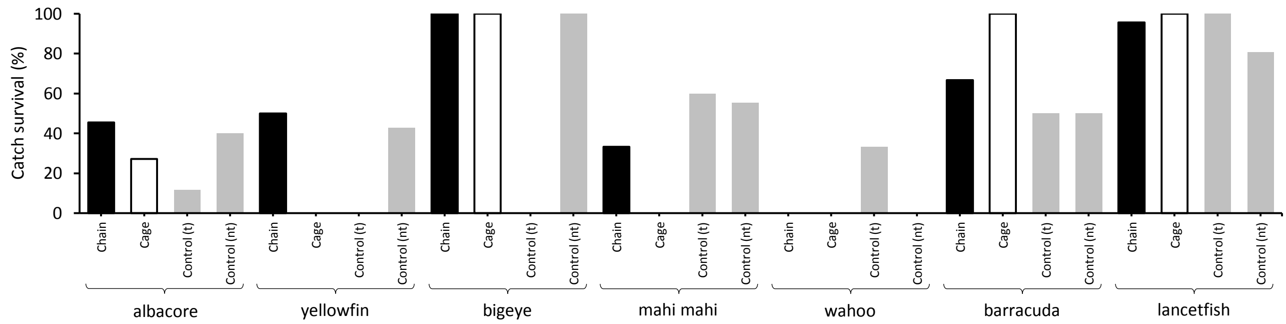
Figure 6 Summary of means size (cm with SE) of the seven most frequently caught fish across experimental (t) gear (treatment branchlines with either the *Cage Device* or *Chain Device* attached, or control branchlines with no device attached) and non-experimental (nt) gear (all are control branchlines without device attached). Collected during pelagic longline sea trials in Australian and Fijian EEZs to determine the effect of developmental *Cage device* and *Chain device* on odontocete depredation and by-catch on pelagic longlines. Results are presented by vessel and combined, with the latter also showing sample size.

FV Sarah J (Australian EEZ, June 2011 – data not collected)

FV Solander 14 (Fijian EEZ, November 2011 – 7 sets, 8,628 hooks)



FV Sea Knight (Fijian EEZ, December 2011 – 6 sets, 7,097 hooks)



Combined results (2 vessels, 13 sets, 15,725 hooks)

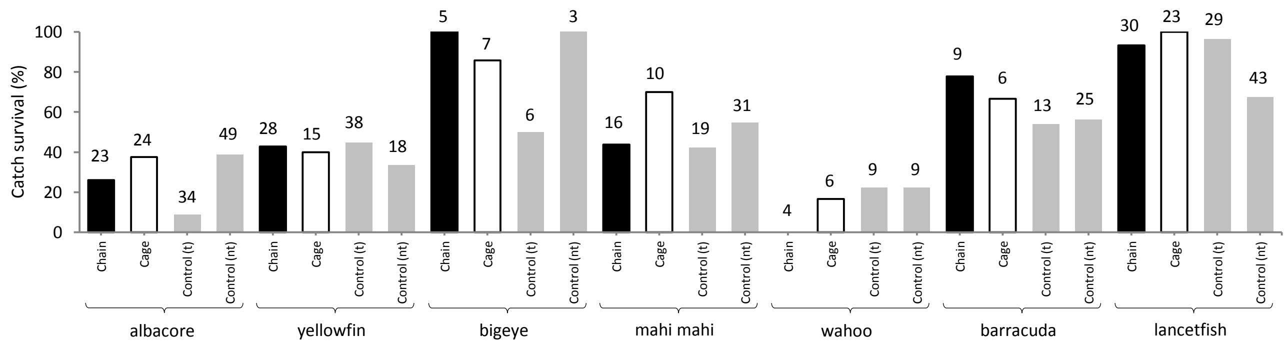


Figure 7 Summary of catch survival (percentages) of the seven most frequently caught fish across experimental (t) gear (treatment branchlines with either the *Cage Device* or *Chain Device* attached, or control branchlines with no device attached) and non-experimental (nt) gear (all are control branchlines without device attached). Collected during pelagic longline sea trials in Australian and Fijian EEZs to determine the effect of developmental *Cage device* and *Chain device* on odontocete depredation and by-catch. Results presented by vessel and combined, with the latter also showing sample size.

Figure 8 Crewmember holding branchline with triggered Cage device over caught and undamaged yellowfin tuna. Note the activating mechanism has moved toward the hook and the head of the caught fish and that the functional deterrent structure is shrouding the fish. The device works on the premise that the functional deterrent structure will either physically or psychologically deter a depredating odontocete. Note also the yellowfin tuna on the deck in the background, which has been depredated by a shark; it was caught on a branchline without a deterrent device attached.

4. DISCUSSION

Previous studies have characterised and quantified operational interactions between odontocetes and fishing gear, although few have attempted to test and quantify potential mitigation devices, with this being the first in the pelagic longline fishing industry. During this study, considerable effort was expended in developing the design and testing the efficacy of the two devices, with a view to mitigating odontocete by-catch and depredation at the hook during all stages of the fishing event (i.e. set, soak and haul). However, despite indications of widespread concern relating to the impact of by-catch on odontocete populations and of depredation on longline fisheries (e.g. Donoghue et al., 2003; Gilman et al., 2006; Hamer et al., 2012), they were rare during these sea trials. Although this could be interpreted as indicating an unexpectedly low level of operational interactions in the region of the sea trails, it is more likely to reflect variability in time and space and the associated lack of data to account for this. In general, the low sample size caused by the low number of events hindered statistical interpretations of the results, especially those relating to the success of the two developmental devices in mitigating odontocete by-catch and depredation. As such, it was not possible to address the question of whether or not the concept of physical and psychological deterrence is valid. Despite this shortfall, several other aspects of the study provided useful insights into whether the implementation of this technology is realistic, from a practical and an economic perspective, which also need to be addressed adequately before uptake in the pelagic longline industry could be expected.

4.1 Impact of devices on odontocete by-catch

Only one by-caught odontocete was recorded during the sea trial, which occurred on a branchline without a device attached. Although a very low sample size, the capacity of the devices to deter odontocetes should not be discounted. This situation prevented robust statistical analysis, although it may have occurred because of spatial and temporal fluctuations in overlap between longlines and odontocetes, with the movement of targeted fish species influencing the movements, effort and strategies employed by both consumers. The fact that by-catch rates recorded during the exploratory trip in 2009 and during one part of the subsequent sea trial in the same location (i.e. both in the Coral Sea) approximately two years later is testament to this fact. There are two ways this problem can be addressed. Firstly, additional sea trials that continue for longer and monitor the activities of more than one fishing vessel (i.e. more observational effort) could assist in capturing these rare events. To date, logistical and financial constraints have prevented this from occurring. Alternatively, inferences could be made about the by-catch and depredation rates in this study when comparing them with previous reports in the literature. However, this would be problematic, due to the differences in time and space, and in the odontocete species involved (Hamer et al., 2012).

Despite the low level of observed by-catch, the impact on odontocete species remains unclear. The size, structure, range and status of most populations is poorly understood, although many species previously believed to be genetically homogenous are now known to be a series of smaller and sometimes geographically isolated populations (Fullard et al., 2000; Bilgmann et al., 2007; Foote et al., 2011). Small populations that depredate from pelagic longlines are, by comparison, more likely to suffer adversely from by-catch related losses. While this highlights the need to manage small odontocete populations as 'units', it should be acknowledged that continued development of physical and psychological deterrent technologies, such as those under development in this study, could assist in addressing this problem.

Many by-catch events are likely to go unobserved using conventional observer methods, because they occur at depth or at distance from the vessel. For example, some depredating individuals may become by-caught and drown, then break away from the gear due to their considerable weight. Others may become temporarily by-caught and then escape, having consumed fishing gear along with caught fish (which is analogous with an entanglement), thus resulting in injuries and possibly death (Secchi et al., 2005; Kock et al., 2006; Bigelow et al., 2011). A recent study of Australian sea lion *Neophoca cinerea* by-catch in a demersal gill-net fishery indicated that although observed by-catch was rare, an unknown proportion of unobservable by-catch was likely to be occurring, because drowned individuals fell out of the gear (Hamer et al., in press) and because entanglements were frequently observed at breeding colonies (Page et al., 2004). Therefore, the widespread concern about the perceived impact of operational interactions on odontocetes in pelagic longline fisheries may be justified, when considering the potential occurrence of unobserved by-catch and entanglements (Donoghue et al., 2003; Gilman, 2011). The four by-caught odontocetes observed during this study fit into this category, because their fate after being released with an entanglement is unknown.

Many odontocete populations are known to migrate over large distances in pursuit of migratory prey fish species such as tuna (Culik, 2004), although the presence of fishing activities may attract particular attention, because they sometimes offer an easily obtainable food source (Soto et al., 2008; Aoki et al., 2012; Hamer et al., 2012). Killer whales in waters adjacent to Tasmania (Australia) may have adapted their migration patterns to habitually foraging for some part of the year from a demersal longline fishery for blue-eye trevalla *Hyperoglyphe antarctica* (AFMA, 2005). Odontocetes are intelligent and are able to adapt their foraging strategies to take advantage of emerging food sources, which in some cases may be related to the frequency of opportunities (Hamer et al., 2008). In this context, the intelligence and adaptability suggests the developing of by-catch and depredation mitigation strategies is likely to be challenging and may need to be ongoing, even when a particular strategy appears to be successful in the first instance. For example, new evidence from the Chilean Patagonian toothfish fishery indicates that sperm whales, previously deterred from depredating by the net sleeve, may have learned how penetrate the barrier and access caught fish (Moreno et al., 2008; Carlos A. Moreno, pers. comm.). These situations are likely to arise more frequently as the burgeoning human population places greater demands on fish stocks and competition with odontocetes for this limited resource becomes more intense, thus highlighting the need to periodically assess mitigation strategies.

Physical and psychological deterrence technologies operating at the hook have the potential to offer immediate and significant conservation benefits and their assessment can be assessed based on the occurrence of by-catch and depredation (Moreno et al., 2008; Hamer et al. 2012). Additionally, the devices under development in this study are designed to approach the problem using physical and psychological deterrence simultaneously, which it was hoped will increase the chance of successfully mitigating odontocete by-catch and of depredating by subscribing to the premise that a 'toolbox' of strategies is needed to address the problem (Hamer et al., 2012). In contrast, although development of acoustic technologies has received more attention, their efficacy is less obvious and thus more difficult to assess, because the response of approaching odontocetes can be unclear (Mooney et al., 2009). Additionally, acoustic devices are generally too large to deploy at the hook (Shapiro et al., 2009), thus are unable to efficiently address the problem of sound attenuation and to minimise their effect on the broader environment (Morton and Symonds, 2002).

Beyond the hook and the vessel, broader management mechanisms in the form of marine protected areas (MPAs) have been proposed as a method of mitigating odontocete by-catch. This approach is likely to become more prevalent as changing societal values demand greater protection for marine mammals (Hooker and Gerber, 2004; DEH, 2005). However, many odontocete populations migrate over vast areas and are likely to move outside existing MPAs for substantial periods each year (NCEAS, 2001; Gerber et al., 2005). In summary, the low level of by-catch reported in this study may be attributable to an unknown proportion of events going unobserved, or to seasonal variation in the level of geographic overlap. This situation may be addressed by continuing this study and increasing the level of observational effort on longline vessels during controlled experimental sea trails.

4.2 Impact of devices on odontocete depredation and fishing operation

Characterising depredation was hindered for the same reason as for by-catch; only four fish were involved, being landed during one fishing event. Despite this, the high number of fish caught during this study revealed that a slightly higher rate of fish catch was recorded on treatment branchlines compared with control branchlines in the experimental section. Similarly, a slightly higher fish catch rate was recorded on control branchlines in the experimental section, compared with the non-experimental section where all branchlines were effectively controls. As such, the presence of a device on a branchline may have resulted in depredating odontocetes being physically or psychologically deterred from approaching and thus depredating caught fish, or alternatively may be attracting more fish.

The fact that more fish were caught per hook on control branchlines in the experimental section compared with branchlines in the non-experimental section suggests that the deterring capacity of the devices may extend beyond the branchline they are attached to. This phenomenon is referred to as the 'edge effect' and has often been used to describe the effect of an edge of fragmented environment on resident individuals, populations, or species (e.g. Kiffner et al., 2009). This term provides context here, because the presence of a device on one branchline appears to have a measurable influence on the ability of an adjacent 'unprotected' branchline, only 30 m or so away, to catch and retain fish. Alternatively, this outcome may indicate that increased fish catch rates are a proxy for increased deterrence of depredating odontocetes by the devices, with individuals being unable to remove caught fish or deter them from becoming caught.

Two mechanisms could lead to this outcome. Firstly, depredating odontocetes may be physically unable to access caught fish in the presence of the deterrent structure, although this can only occur where devices are actually present (Moreno et al., 2008). Secondly, depredating odontocetes that have had a prior unpleasant experience with tangled longline fishing gear, such as temporary entanglement and subsequent injury, may be psychologically deterred from approaching caught fish on branchlines that have a device attached. Such an encounter may elicit a stronger level of deterrence that may encourage the odontocete to leave the area altogether, thus effectively extending the influence of the deterrent device to adjacent control branchlines (Kock et al., 2006). Therefore, the devices may not need to be placed on every branchline to effectively deter depredating odontocetes, thus markedly reducing the cost of implementation.

Although few instances of depredation occurred during this study, there is sufficient evidence worldwide to demonstrate that many pelagic longline fisheries experience substantial financial losses over the long term (Hamer et al., 2012). Effective fishery management may also be hindered by the activities of depredating odontocetes, because they partially or completely remove fish, or discourage fish from taking a baited hook in the first place. Overfishing may occur in the short term, because fishers are unlikely to record damaged fish that are discarded and because fish that are completely removed during depredation are not observed, thus negatively biasing official catch records (Hamer et al., 2012). Alternatively, under fishing may occur in the longer term, because the catch per unit effort (CPUE) artificially drops below levels deemed to be sustainable, thus encouraging fishery managers to reduce the total allowable commercial catch (TACC).

It should be noted that each of the approximately 250 units of each of the two devices was deployed during each of the 23 fishing events. During the design phase of the Cage device and Chain device, maximising durability and minimising maintenance were important considerations. Aside from the occasional loss of units along with general gear failures during the sea trials, there were no records of design related damage or fatigue to units that were not triggered. The ‘real world’ sea trials provided opportunities to identify design aspects that would benefit from further improvements. Specifically, improvements could be made to the trigger and to the one-way cam system to provide a ‘softer’ contact with the branchline, thus minimising the possibility of branchline damage. The design of both devices facilitated routine adjustments and repacking of the deterrent structures to be made simply and swiftly. On rare occasions when triggered cage structures sustained minor damage, mostly due to the escape attempts of large fish or sharks that had been caught, repairs were again simple and swift. This was mostly because the cage structure utilised the materials and tools used to construct and repair the fishing gear (i.e. monofilament longline and aluminium swages), thus being familiar to the crewmembers. Minimal maintenance loads, plus the simplicity of repairs minimised the chance that faulty or inefficiently operating devices would be deployed, being a critical element in ensuring the results obtained were an accurate reflection of the situation at each hook.

Setting and hauling times were minimally affected by the introduction of devices to the fishing operation. Vessel and mainline deployment speeds were predetermined by the Master in order to ensure that the longline and baited hooks were correctly suspended in the water column, leading to the need for an extra crewmember during setting to ensure the devices were properly attached and deployed. The devices also had minimal impact on hauling speeds, despite initial concerns that removing, repairing and storing the devices would result in considerable delays. It became evident during the sea trials that crewmember fatigue may have had a greater impact on hauling speed than the presence or absence of the devices on branchlines. Although the order in which the experimental and non-experimental sections were hauled was alternated, it was found that the section hauled first generally took slightly less time to complete than the section hauled last, even though the numbers of branchlines being hauled was similar. In general, the added responsibility of deploying and retrieving the devices each fishing event had a negligible impost on 'normal' fishing operations once crewmembers became familiar with the required methods. The main difference was the need for an extra crewmember during setting and hauling to handle the devices. Although this may not be of concern to Fijian longline companies who are able to hire crew at minimal cost, this need may be a significant cost in countries like Australia where the cost of hiring crew is comparatively high. Nonetheless, initial indications are that the implementation of the devices into the fishing operation may increase fish yields and thus income to the vessel, which in an ideal situation would more than offset the additional costs associated with hiring an extra crewmember.

4.3 Advice for future development and implementation

This study made considerable inroads into the design and development of two options for physically and psychologically deterring depredating odontocetes. Unfortunately though, logistical and financial constraints prevented the collection of a sufficient amount of data to prove or otherwise the concept that the devices were effective in this capacity, although initial indications suggest this approach is worthy of further consideration. Providing further encouragement is the positive integration of the devices into the fishing operation and the negligible effect on the catch rate, survival and size of target fish. These results suggest the two designs are sufficiently developed to provide the basis for further sea trials to confirm their efficacy as a deterrent to depredating odontocetes. Specifically, the effort involved needs to be considerably large across time and space to ensure that enough of the relatively rare by-catch and depredation events are observed. Based on a fundamental rule in statistical analysis that suggests at least 30 observations of the event of interest need to be recorded (Quinn and Keough, 2002), the data collected so far indicates that between 359,948 hooks (using only sea trial data: one by-catch event and 20,163 hooks) and 604,890 hooks (using both exploratory and sea trial data: four by-catch events and 47,993 hooks) need to be set to obtain sufficient data to enable robust statistical analyses. In practice, this equates to the need to monitor at least 360 fishing events. Of course, this approach assumes that the by-catch rates would remain the same as more data is collected, although this is unlikely to be the case due to the aforementioned heterogeneity in the activities of odontocetes and longline fisheries in time and space. Therefore, a sensible approach may be to monitor a further 100 fishing events, or 100,000 hooks, then reassess the ability to conducts robust statistical analyses on the data obtained.

Despite the positive progress made in this study and the potential to produce two devices that successfully deter depredating odontocetes from approaching pelagic longlines, their widespread use is unlikely to occur unless there are obvious financial benefits in doing so. Attempts were made during the design phase to minimise the per unit cost of manufacturing of the devices, in part through discussions with the manufacturers and through the incorporation of existing fishing gear materials. Large scale manufacture of devices would also result in per unit cost reductions, although this is still on the horizon, rather than being imminent. The richer industrial longline fisheries that see the longer term economic benefits in implementing this technology are more likely to wear the short term cost of retrofitting vessels and fleets. However, this is unlikely to be the case for the poorer artisanal fisheries that operate on comparatively modest and short term budgeting plan. Whatever the case, if these devices are proven to be successful at deterring odontocetes, then there is a subsequent imperative to minimise the per unit cost of production to encourage voluntary implementation. While fishery managers in some countries may be effective in mandating the use of such technology and then monitoring uptake and compliance, a large proportion of the global pelagic longline fishing effort is illegal, unregulated and unreported (IUU; FAO, 2001). If the impact that odontocete depredation is to be addressed properly, then IUU pelagic longline fisheries have to be considered in the solution. All stakeholders, particularly those with financial interests in pelagic longline fisheries, are encouraged to conduct cost-benefit analyses to determine how much they should invest in odontocete deterrent technologies. Specifically, calculations should include best and worst case scenarios for the (i) value of the fish species targeted, (ii) cost of depredation, (iii) overall running cost of the fishing operation (iv) reported success rate of the available mitigation technologies and (v) practical implementation of those technologies. Therefore, if this technology is indeed found to successfully deter depredating odontocetes, then it will also be possible to determine how cheap they need to be in order to bring about widespread implementation. If realised, this outcome would have widespread and significant conservation and welfare benefits for the depredating odontocetes and populations involved and economic benefits for the pelagic longline fisheries involved.

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