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Upcycled glass and plastic bottles offer potential low-cost mitigation to megafauna bycatch in gillnet fisheries

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ABSTRACT

Bycatch in gillnet fisheries represents the primary threat to cetaceans globally, yet mitigation has been hampered by a lack of effective, affordable solutions. Here we tested upcycled glass and plastic drink bottles as low-cost bycatch mitigation devices (mechanical pingers and acoustic reflectors, respectively) in gillnet fisheries across three regions. Observed trials were conducted in surface-set driftnet fisheries targeting teleosts and elasmobranchs off Zanzibar, East Africa, and Peru (2017–2021), and in bottom-set trammel net fisheries targeting teleosts off Brazil (2020–2022). Glass and plastic bottle treatments were tested against control sets across 1107 and 456 drift net sets in Zanzibar and Peru respectively, and 105 trammel net sets in Brazil. Catch differences between treatment and control sets were analysed using generalised linear hurdle and mixed models. Plastic bottles showed promise in Brazil, potentially reducing dolphin bycatch while increasing fish catch, though further trials are needed to confirm this. In Peru, glass bottles had no effect on dolphin, porpoise, or turtle bycatch but altered elasmobranch and teleost catches; plastic bottles similarly had no effect on dolphin bycatch but increased shark catch. In Zanzibar, no dolphin bycatch was recorded in any sets, though plastic bottles increased tuna catch. Overall, our results suggest plastic bottles may reduce dolphin bycatch in bottom-set fisheries, but neither device showed efficacy in surface-set fisheries. We encourage further trials of these and similar low-cost devices as accessible mitigation tools for small-scale fisheries.

1. Introduction

Bycatch poses the single largest threat to cetacean populations at the global level (Read et al., 2006). Despite this, bycatch assessment and mitigation do not attract proportionate levels of research effort, practical implementation, or the political will to make effective progress (Lewison et al., 2004; Read et al., 2006; Reeves et al., 2013; Berggren and Kiszka, 2015; Anonymous, 2017; Wade et al., 2021). Most mitigation efforts to date have been restricted to large-scale commercial fisheries in developed countries, whereas many bycatch problems occur in small-scale fisheries (SSF) in developed (Rogan et al., 2021) and developing countries where they are largely overlooked (Lewison et al.,

2014; Temple et al., 2021; Svarachorn et al., 2023). Our understanding of SSF is severely restricted by their dispersed and often informal nature, their magnitude, and a general lack of data in many regions (Komoroske and Lewison, 2015). Consequently, bycatch levels and impacts on cetacean populations are poorly quantified. Despite this, SSF are predicted to be the most impactful to coastally occurring cetaceans (Temple et al., 2021; Temple et al., 2024), both migratory and resident species, many of which are already facing extirpation or extinction (e.g., vaquita (*Phocoena sinus*), franciscana (*Pontoporia blainvillei*), and Māui dolphin (*Cephalorhynchus hectori maui*). Of the fishing gears used by both large-scale and SSF, bottom-set, surface-set, and driftnets, both monofilament and multifilament, pose the greatest bycatch risk to cetaceans

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(FAO, 2018), thus it is these gears where priority actions must be taken.

Cetaceans primarily use sight and sound (odontocetes) to navigate in their environments (Kastelein et al., 2000). It is these senses that dictate cetaceans' ability to detect the presence of fishing gears and how they interact with them. Existing bycatch reduction technologies for small cetaceans (odontocetes except for the sperm whale, *Physeter macrocephalus*) have largely focussed on the acoustic component, with electronic alarms ("pingers") that have reduced gillnet bycatch rates in some dolphin species and the harbour porpoise (*Phocoena phocoena*) (Kraus et al., 1997; Caretta et al., 2008; Hamilton and Baker, 2019; Lucas and Berggren, 2023). Though pingers have not been universally successful (Mangel et al., 2013), which may undermine widespread use. Electronic pingers are now mandated in some developed country fisheries (e.g., EU gillnets vessels > 12 m, EU Regulation 1241, 2019), though not all are strictly enforced, and very few are implemented in SSF. The primary barrier to pinger implementation, and indeed the implementation of any other potential solution, in SSF is cost. Commercially available pingers cost US\$35–100 per 100 m of net, which is prohibitively expensive for most small-scale fishers, particularly in developing countries. Further, fishers have raised concerns about potential effects on target species catch and a "dinner-bell" effect with resultant increases in depredation from marine mammals (Bordino et al., 2002).

This relative lack of success in effectiveness and implementation of acoustic pingers highlights the attributes driving cetaceans' perception of their environment. If the emission of sound as mitigation is not universally effective, should other aspects of perception be exploited, either individually or in tandem with the pinger effect, to increase effectiveness across a wider range of species? Odontocetes use echolocation to navigate and detect objects in their environment. Successful detection of objects is influenced by the sound frequency and acoustic backscatter properties of a given object (Au and Jones, 1991). Gillnet backscatter is typically too weak for many odontocetes to reliably detect gillnets at sufficient range to avoid entanglement, as evidenced from modelling target strength of different types of gillnets and echolocation properties of dolphins and harbour porpoise (Kastelein et al., 2000). Therefore, one strategy to reduce bycatch of odontocetes would be to increase the acoustic backscatter properties of gillnets, without compromising the net itself. This has been tested by adding acrylic spheres to gillnets to enhance acoustic reflection which has shown promising results from pilot trials in reducing harbour porpoise (*Phocoena phocoena*) bycatch in gillnets (Kratzer et al., 2021).

Other potential bycatch mitigation methods include light emitting diodes (LED) lights. LEDs were trialled on driftnets in Peru where they reduced dolphin bycatch without negatively affecting target catch (Bielli et al., 2020). Although potentially cheaper initial cost of using LEDs compared to acoustic pingers, LEDs may still be unaffordable to developing country small scale fishers given the number of lights required if recommended 10 m spacing is used (Bielli et al., 2020). Further, the ecological effect of illuminating marine environments during hour of darkness need to be considered before wider application.

In this project we developed and tested two potential low-cost mitigation solutions to dolphin and porpoise bycatch, made from up-cycled locally available materials which would otherwise constitute waste – glass bottle acoustic pingers and plastic bottle acoustic reflectors (Berggren, 2015; 2017). The two potential solutions represent a different strategy (sound and echolocation efficiency, respectively) to alert cetaceans to the presence of nets, with potential for combined or separate application depending on local and environmental conditions. The aims of the study were to test the effect of the glass and plastic bottles on the bycatch of dolphin, porpoise and target species catch by conducting observed trials in surface-set driftnet fisheries in Zanzibar, Tanzania and off Salaverry, Peru, and a bottom-set trammel net fishery off Torres and Passo de Torres, Brazil.

2. Methods

2.1. Development of the potential low-cost bycatch reduction methods

2.1.1. Glass bottle pinger

First, we aimed to develop a low-cost acoustic pinger, intended to mimic the effect of commercially available pingers. Up-cycled 300–350 ml glass drink bottles were fitted with a steel bolt (40 mm length with hexagonal head) suspended on a string inside the bottle attached to a rubber stopper (Fig. 1a). When the bottle moves the string inside acts as a pendulum to provide mechanical amplification, allowing the bolt to swing in response to minimal movement of the bottle. When the bolt hits the side of the bottle it produces a clinking sound. The acoustic properties of the glass bottle pinger were measured in an anechoic testing tank (3 m x 3 m x 1.5 m) at Newcastle University, UK (Fig. 1b). The sound from the glass bottle was measured while suspended in the tank 0.5 m from a broad-band calibrated Reson TC4032 hydrophone connected to a VP2000 preamplifier and digital storage oscilloscope. Motions were manually induced to simulate the bottle being attached to the headrope of a net in low sea state. For comparison, we also tested one of the most common 10 kHz commercial electronic pingers (Fumunda/Future Oceans 10 kHz pinger) under the same conditions.

The recorded sound from the glass bottles had a mean of 120 dB (95% CI 117–123 dB) re 1 μ Pa/ $\sqrt{\text{Hz}}$ @ 1 m at 10 kHz). In comparison, the commercial pinger emitted a 300 ms duration harmonic series with 10 kHz fundamental frequency, every 4 s, with a maximum spectral density of 132 dB (95% CI 120–145 dB) re 1 μ Pa/ $\sqrt{\text{Hz}}$ @ 1 m. The signal from the glass bottle pinger was significantly shorter duration with the energy spread over a wider spectrum, including below 5 kHz (Fig. 1c).

2.1.2. Plastic bottle acoustic reflectors

Second, we aimed to develop a low-cost acoustic reflector. One of the strongest sonar targets in water is an air bubble due to the acoustic impedance mismatch at the air-water interface. The plastic material of the bottle has similar acoustic impedance to water and hence the acoustic backscatter from a plastic bottle exposed to sound in water would mainly result from the air inside the bottle. The acoustic backscatter of different size plastic bottles (500 ml and 2000 ml) was measured by submerging bottles in the anechoic testing tank and transmitting a synthesised typical dolphin echolocation signal, a broadband "click" signal centred on 70 kHz, and recording the sound reflected by the plastic bottles (Fig. 1d). The same recording equipment and distance was used as described above for the glass bottles.

The plastic bottles produced strong acoustic backscatter of the simulated dolphin 70 kHz broadband pulse simulating an echolocation click (Figs. 1d and 1e). The 500 ml and 2000 ml bottles had a –27 dB and –16 dB target strength, respectively. A gillnet has a typical target strength of –62 to –46 dB (Au and Jones, 1991) indicating that plastic bottles represent a 100–1000-fold increase in target strength (dB is a logarithmic scale). Dolphins may detect gillnets at distances between 25 and 55 m in low noise environments (Kastelein et al., 2000), but the detection distance may be substantially reduced in high-noise environments (e.g., natural and anthropogenic noise levels) and among species.

2.1.3. Selecting fisheries for the mitigation trials

Small cetacean bycatch occurs globally in small-scale surface-set driftnet fisheries, bottom-set trammel net and bottom-set gillnet fisheries. To maximise the value of trials for the up-cycled bottles we explored fisheries meeting the following conditions:

1. The fishery is small-scale and operates either surface-set driftnets or bottom-set trammel nets or gillnets.
2. The fishery has an available estimate of dolphin Bycatch Per Unit Effort (BPUE).

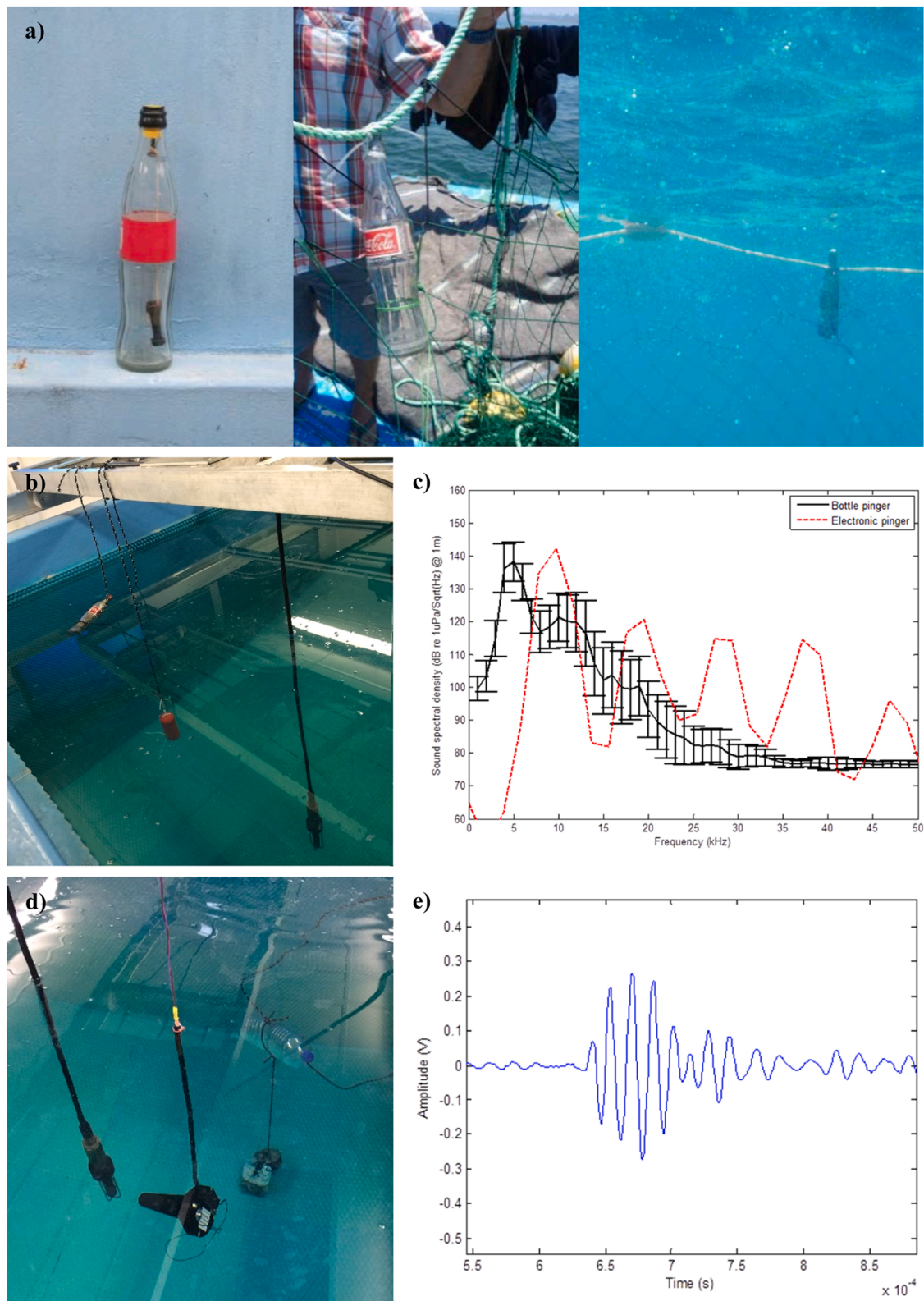


Fig. 1. Up-cycled glass bottle pingers and plastic bottle acoustic reflectors. **a)** The glass bottle pinger is a regular 350 ml glass drink bottle with a bolt suspended inside by a string attached to the stopper. The bottles are mounted vertically on the net head rope and when the bottle moves, the string acts as a pendulum making the bolt hit the side of the bottle producing an acoustic signal. **b)** The acoustic properties of the glass bottle pinger were measured in an anechoic testing tank (3 m x 3 m x 1.5 m). **c)** Measurements of glass bottle pinger acoustic output of 120 dB (95% CI 117–123 dB) re 1 μ Pa/ $\sqrt{\text{Hz}}$ @ 1 m at 10 kHz (black line). For reference output of Fumunda (FutureOceans) 10 kHz pinger, 300 ms ping every 4 s, source level at 10 kHz, 132 dB re 1 μ Pa/ $\sqrt{\text{Hz}}$ @ 1 m (red dotted line). **d)** The backscatter of plastic bottles was tested in the anechoic testing tank. **e)** A 500 ml plastic bottles produced -27 dB acoustic reflection = a 100–1000 fold increase in target strength compared to gillnets (-62 to -46 dB) when subjected to a transmitted 70 kHz broadband pulse simulating a dolphin echolocation click.

3. Fishers willing to participate and to have independent observers on their vessels.

Three fisheries were selected for the trials; a coastal driftnet fishery off Zanzibar, Tanzania, an offshore driftnet fishery off Salaverry, Peru, and a trammel net fishery off Torres and Passo de Torres, Brazil.

2.2. Bycatch mitigation trials

2.2.1. Trials off Menai Bay, Zanzibar, Tanzania

Glass bottle pinger and plastic bottle acoustic reflectors were tested in the surface-set driftnet fishery off Zanzibar, Tanzania (Fig. 2a) during January–March 2017. This driftnet fishery uses small (6–10 m) sail and/or outboard powered boats fishing with a single 400–1100 m multifilament (7 × 7 cm mesh size) net, which is set and hauled by hand. The fishing is conducted at night and the soak time is 5–8 h (Table 1). The main target species for the fishery are large pelagic finfish, specifically tuna (*Euthynnus affinis* and *Katsuwonus pelamis*), billfish (*Istiophorus platypterus*, *Makaira indica* and *Xiphias gladius*), and kingfish (*Scomberomorus commerson*). Previous observer programmes indicate a bycatch rate of 0.02 Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) per driftnet haul, with approximately 10% of the population removed by fisheries bycatch in driftnets in 2003–2004 and 2007–2008 (Amir, 2010). Previous trials with electronic pingers (Fumunda/Future Oceans 10 kHz pinger) in the same fishery in 2007/2008 reduced the catch of Indo-Pacific bottlenose dolphins, indicating that acoustic pingers may be effective to mitigate dolphin catch (Amir, 2010). However, to date acoustic pingers have not been implemented in this fishery with cost stated by participating fishers as the main barrier to implementation.

We held workshops (e.g., Fig. 3a) with fishers based in two villages (Kizimkazi Dimbani and Kizimkazi Mkungoni) to introduce the project and solicit participation, with 36 vessels agreeing. Vessels were randomly assigned treatments: (1) control, fishing without any modification; (2) attaching 350 ml glass bottle pingers vertically in the net every 50 m on the floatline; or (3) attaching 500 ml plastic bottle reflectors every 50 m on the sinkline of the net. For the latter treatment a small weight (coral rock) was attached on the sinkline next to the plastic bottle to compensate the buoyancy and maintain the hanging ratio of the net. Glass bottles were attached to the floatline (e.g., Fig. 3b) to facilitate bottle movement with wave action, plastic bottles were attached to the sinkline to reduce disturbance from surface waves on bottle target strength. Each vessel was randomly assigned an onboard observer to record effort (start and end time of the set, soak time and start and end times for the haul) and catch (including photos for species identification). Assuming a bycatch rate of 0.02 dolphins per haul the required sample size per treatment to achieve and 80% power to detect a 50%, 75%, or 90% reduction in bycatch occurrence is estimated as 1826, 677, and 414, respectively.

2.2.2. Trials off Salaverry, Peru

Glass bottle pingers (March 2019–January 2020) and plastic bottle acoustic reflectors (August 2020–November 2021) were also tested in a surface-set driftnet fishery off Salaverry, Peru (Fig. 2b). In this fishery small-scale vessels (<15 m), use multifilament 3000 m driftnets (14–22 m height, 8 in. mesh size). The fishing area for these vessels is up to 100 nm off Salaverry and vessels remain at sea for one or more weeks (a fishing trip). Each trip has multiple sets and nets are set in the afternoon and have an average of 20 h soak time (Table 1). The fishery targets elasmobranchs (class Elasmobranchii, mainly sharks), but also catches dolphinfishes (*Coryphaena* sp.), billfishes (*Xiphias* sp.), and bonito (*Sarda* sp.) (Alfaro-Shigueto et al., 2010; Mangel et al., 2010). The bycatch rate of small cetaceans (*Phocoena spinipinnis*, *Tursiops truncatus*, *Lagenorhynchus obscurus* and *Delphinus* sp.) in this fishery has been estimated as 0.34–0.65 animals per set, equivalent to 3–5 animals per trip (Mangel et al., 2010, 2013). Previous trials in this fishery with 10 kHz acoustic pingers demonstrated a significant reduction (–37.2%) in the

bycatch of dolphins and had no significant impact on elasmobranch target species catch (Mangel et al., 2013). However, following the trial there has been no implementation of pingers in the fishery with the main reason being cost of purchasing and maintenance of the devices.

An initial workshop (e.g., Fig. 3a) was held in Salaverry on 6 March 2019 when we met the local fishers to introduce the trial and the up-cycled bottles that would be used, with two vessels agreeing to participate. Each vessel randomised their trial effort per fishing trip (control=no bottles on the net or treatment=glass bottles attached to the net) by tossing a coin prior to the trip. The randomisation was done in pairs so if the first coin toss resulted in a control trip, then the following trip was treatment. The outcome for the next two trips was then decided by a new coin toss. Vessels were either control or treatment for the duration of each trip. The types of bottles which could be used were discussed with the fishers and, after considering the available options, a 350 ml glass bottle (soft drink or beer bottle) and 1500 ml plastic (water drink bottle) were chosen. Final decisions regarding attachments of the bottles and other logistics for the trials were made in discussion with participating fishers. The glass bottle pingers were mounted vertically with the neck of the bottle tied to the net headrope and the bottom of the bottle to the net mesh (e.g., Fig. 3b). Bottles were attached every 93 m on average (±5 m) on the headrope of the driftnet. The plastic bottles acoustic reflectors were spaced 50 m and attached in the centre of the net panel (e.g., Fig. 3c). Ballast was required to prevent them from deforming the nets, this was achieved by adding sand in the bottles resulting in a reduction of approximately 167 ml of air volume. Given the large size bottles used (1500 ml), the reduction in air volume would have had limited effect on the overall backscatter produced by the bottles. Each vessel had an independent observer aboard that recorded fishing effort and catch during all sets. Assuming a bycatch rate of 0.34 dolphins per haul the required sample size per treatment to achieve and 80% power to detect a 50%, 75%, or 90% reduction in bycatch occurrence is estimated as 80, 31, and 19, respectively.

2.2.3. Trial off Torres and Passo de Torres, Brazil

Lastly, plastic bottle acoustic reflectors were trialled in the bottom-set trammel net fishery off Torres and Passo de Torres, Brazil (Fig. 2c) between November 2020–December 2022. No trials were conducted in Brazil with glass bottle pingers due to their potential to attract pinnipeds and cause depredation on catch (Bordino et al., 2002). This fishery includes 55 vessels (6–20 m) fishing with nets approximately 3000 m long, made up of 50 × 2 m panels with an inner mesh size of 18–20 cm, outer mesh sizes of 60 × 60 cm and soak time of 24 h (Table 1). The fishing is conducted between the coast and the 30 m isobath. The target fish are the Brazilian flounder (*Paralichthys* spp.) and whitemouth croaker (*Micropogonias furnieri*) (Larre et al., 2019). The estimated bycatch rate for this fishery is 0.28 dolphins/set (Larre et al., 2019). Several methods have been tested to reduce *Pontoporia blainvillei* bycatch in other gillnet fisheries, including electronic pingers, increased acoustic reflectivity of gillnets by infusion of barium sulphate (BaSO₄) and increased stiffness of the gillnet nylon twine (Bordino et al., 2002; 2013; Berninsone et al., 2020). Despite some success, there have been no implementation of these methods in the small-scale fisheries in the species' range.

An initial workshop (e.g., Fig. 3a) was held in November 2020 with local fishers to discuss using plastic bottle reflectors as a potential mitigation method to reduce dolphin bycatch in the bottom-set trammel gillnet fishery off Torres and Passo de Torres, southern Brazil (Fig. 2c). Two vessels participated in the trial. Trial effort was randomised per each fishing trip (control = no bottles on the net, treatment = upcycled plastic drink bottles attached to the net) by tossing a coin prior to the trip. The randomisation was done in pairs so if the first coin toss resulted in a control trip, then the following trip was a treatment. The types of bottles which could be used were discussed with the fishers and, after considering the available options, it was decided to use a 250 ml plastic bottle (water drink bottle). Decisions were also made regarding attachments of the bottles and other logistics for the trials. Up-cycled



Fig. 2. Trial locations for up-cycled glass bottle pingers and plastic bottle acoustic reflectors. a) Global distribution of trial locations. b) Glass bottle pingers and plastic bottle acoustic reflectors trials were conducted in the surface-set driftnet fishery of Salaverry, Peru (8°12'S, 78°58'W). c) Plastic bottle acoustic reflectors trials were conducted in the bottom-set trammel net fishery of Torres and Passo de Torres, Brazil (29°19'S, 49°43'W). d) Glass bottle pingers and plastic bottle acoustic reflectors trials were conducted in the surface-set driftnet fishery of Menai Bay Conservation Area, Zanzibar, Tanzania (6°29'S, 39°29'E).

Table 1

Net configuration, drink bottle specification and target catch species in bycatch mitigation trials in Brazil, Peru and Zanzibar (Tanzania).

	Net length	Soak time	Bottle size	Bottle spacing	Target catch
Brazil	(m)	(hrs)	(ml)	(m)	
Bottom-set trammel net	3000	24	Plastic 250	130	Flounder and Croaker
Peru					
Surface-set	3000	20	Glass 350	93	Elasmobranchs
driftnet			Plastic 1500	50	
Zanzibar					
Surface-set	400-	5–8	Glass 350	50	Pelagic finfish
driftnet	1100		Plastic 500	50	

plastic 250 ml plastic drink bottles with air, but with no added weights, were used as acoustic reflectors attached every 130 m on the headline of the bottom-set trammel net. Each fishing trip had an independent on-board observer that recorded the fishing location, soak time, environmental conditions and catch of target species (kg) and dolphins (counts). Assuming a bycatch rate of 0.28 dolphins per haul the required sample size per treatment to achieve and 80% power to detect a 50%, 75%, or 90% reduction in bycatch occurrence is estimated as 103, 39, and 24, respectively.

2.3. Analysis

To assess the impacts of up-cycled bycatch reduction devices on dolphin bycatch events we used Generalised Linear Mixed Models (GLMMs) with the binomial distribution with an offset term for fishing power (kilometre hours of fishing). The exception was when analysing

dolphin bycatch in Brazil, where we used Firth logistic regression due to complete separation in the response (see Results). Firth's logistic regression addresses complete separation by applying a small penalty to the likelihood function, which prevents model coefficients from diverging to infinity and produces finite, interpretable estimates even when one group has no observed events. Target catches in Zanzibar and Peru trials were recorded as count data by species group, whereas in Brazil catch was recorded by weight. To analyse target species catch effects in Zanzibar and Peru trials we used Generalised Linear Hurdle Models, (with truncated negative binomial distribution assumed for the conditional portion of the model), to assess the two-step potential effect of bycatch reduction devices on 1) Hurdle: the likelihood of presence/absence of taxa in driftnet sets (events), and 2) Conditional: the level of catch in those sets (events) where catches were present. This was considered appropriate as it allows for the simultaneous exploration of two potential modes of change in catches that could result from gear modification. In Brazil there were no fishing sets which resulted in zero target catch, we therefore assessed the effect of bycatch reduction devices on this catch using a GLMM with a Gamma distribution. Where possible models included the effect of treatment and the vessel as fixed effects, with crew skill a known driver of target species catch, alongside an offset term for fishing power. Additionally, models for Peru included the declared target species for the trip as a factor and models in Brazil used fishing depth, because these factors may influence the composition of the target catch. In Zanzibar the large number of vessels participating in this trial meant that effect of captain on target species lead to model over-parametrisation, however we instead included month as a variable in the model, which was associated with some changes in vessel participation and changing availability of migratory species in the fishing area. All analyses were conducted using R v4.3.0 within RStudio 2023.03.1 (R Core Team, 2023; RStudio Team, 2023). For all GLMMs we used the R package *glmmTMB* (Brooks et al., 2017). Model residuals were tested for uniformity, under- and over-dispersion, existence of extreme outliers, zero-inflation, and conducted quantile regressions and



Fig. 3. Up-cycled glass bottle pingers and plastic bottle acoustic reflector trials. a) Workshops were held with fishermen in the targeted fisheries to introduce the project and secure participants. b) glass bottle pinger attached to a surface-set driftnet. c) Plastic bottle acoustic reflector attached to a surface-set driftnet. d) dolphin bycatch in a surface-set driftnet during the trial.

scale residuals using the R packages *DHARMA* (Hartig, 2018). Residuals met the required assumptions in all cases.

3. Results

We achieved the following sampling in each trial (Table 2):

- Zanzibar glass bottle pingers and plastic bottle acoustic reflectors: 1107 sets (401 control, 394 glass, 312 plastic).
- Peru glass bottle pingers: 240 sets (120 control, 120 glass).
- Peru plastic bottle acoustic reflectors: 216 sets (121 control, 95 plastic).
- Brazil plastic bottle acoustic reflectors: 105 sets (57 control, 48 plastic).

3.1. Dolphin bycatch

In Brazil, four dolphins, two *Pontoporia blainvillei* and two *Tursiops truncatus*, were recorded as bycatch in the control sets and no animals were bycaught in treatment sets using plastic bottle acoustic reflectors. The occurrence of bycatch appeared to trend lower in nets with plastic bottle acoustic reflectors than in control nets (Firths logistic regression, $\chi^2 = 3.17$, $p = 0.075$, Fig. 4a). The bycatch rates for dolphins were $4/57 = 0.07$ and $0/48 = 0$ per set for control sets and sets with plastic bottle acoustic reflectors, respectively.

In the Peruvian plastic bottle acoustic reflector trials, 12 dolphins (eight *Delphinus sp.*, three *Lagenorhynchus obscurus*, and one *Tursiops truncatus*) were bycaught in control sets and 10 small cetaceans (seven *Delphinus sp.* and three *Phocoena spinipinnis*) were bycaught in sets using plastic bottle acoustic reflectors. In the glass bottle pinger trials, 16 small cetaceans (eight *Delphinus sp.*, five *Phocoena spinipinnis*, one *Grampus griseus*, one *Lagenorhynchus obscurus*, and one *Tursiops truncatus*) were bycaught in control sets and 18 small cetaceans (nine *Delphinus sp.*, three *Lagenorhynchus obscurus*, three *Phocoena spinipinnis*, one *Tursiops truncatus*, and two unidentified species) were bycaught in sets using glass bottle pingers. The occurrence of bycatch was not significantly different between control nets and those with plastic bottle acoustic reflectors (GLMM, $Z = -0.175$, $p = 0.861$, Fig. 4b), nor between control nets and those with glass bottle pingers (GLMM, $Z = 0.098$, $p = 0.922$, Fig. 4c). The overall bycatch rates for small cetaceans were $28/241 = 0.116$, $10/95 = 0.105$, and $18/120 = 0.150$ per set for control sets, sets with plastic bottle acoustic reflectors, and sets with glass bottle pingers, respectively.

In Zanzibar, no dolphins were caught across any of the control or treatment sets, despite an expected bycatch of 8 animals across the 401

control hauls (based on previous observer programme data in the same fishery [401×0.02 dolphin catch/haul]). Thus, no conclusions can be drawn as to the effect of the mitigation devices on dolphin bycatch.

3.2. Target catch

In the Brazilian plastic bottle acoustic reflector trial, a total of 14,347 kg of fish was caught across the 105 sampled net sets, with a median catch of 84.5 kg per set. Catch was not separated by species and so only total weight of catch between control sets and sets with plastic bottle acoustic reflectors was compared. We found that the weight of fish catch was significantly higher when using plastic bottle acoustic reflectors (GLMM, $Z = 2.106$, $p = 0.035$).

In the Peruvian plastic bottle acoustic reflector trials elasmobranchs were declared to be the target group of all 216 sets during the trial, with sharks caught in 86.6% of all sets (totalling 9107 individuals), whereas rays only occurred in 18.0% of sets (totalling 652 individuals). Fish (including billfish, dolphinfish, and bonito) were declared to be a potential target in 116 of the 216 sets but were never declared as the main target, they occurred in only 16.2% of catches (totalling 1003 individuals). As such, we again focussed on sharks and rays as the primary target groups of interest. The occurrence of sharks in the catch was not significantly influenced when using plastic bottle acoustic reflectors (GLMM, $Z = 0.720$, $p = 0.471$), and there was no decrease in the number of sharks caught when they did occur (GLMM, $Z = -0.198$, $p = 0.843$). For rays the effect of declared target species had to be dropped from the model because it was leading to non-convergence, likely a result of over-parametrisation. The occurrence of rays in the catch was not significantly influenced when using plastic bottle acoustic reflectors (GLMM, $Z = 0.929$, $p = 0.353$), and there was no decrease in the number of rays caught when they did occur (GLMM, $Z = -0.046$, $p = 0.963$).

In the Peruvian glass bottle trials elasmobranchs were declared to be the target group of 227 of the 240 sets during the trial, with sharks caught in 87.1% of all sets (totalling 7556 individuals), whereas rays only occurred in 12.9% of sets (totalling 1579 individuals). Fish (including billfish, dolphinfish, and bonito) were only declared to be a target in 31 of the 240 sets and declared as the main target only 14 times, they occurred in only 12.5% of catches (totalling 1202 individuals). As such, we focussed on sharks and rays as the primary target groups of interest. The occurrence of sharks in the catch was significantly reduced when using glass bottle pingers (GLMM, $Z = -2.57$, $p = 0.010$), but there was no decrease in the number of sharks caught when they did occur (GLMM, $Z = 1.10$, $p = 0.272$). As for rays in the plastic bottle trial, the effect of declared target species had to be dropped from the model because it was leading to non-convergence, likely a result of over-parametrisation. The occurrence of rays in the catch was significantly increased when using glass bottle pingers (GLMM, $Z = 3.047$, $p = 0.002$), but there was no apparent increase in the number of rays caught when they did occur (GLMM, $Z = 0.138$, $p = 0.890$).

In Zanzibar, the trial had sufficient information (i.e. photographs of sufficient quality) for 800 sets to analyse target species catch among treatments (307 control, 273 glass bottle pingers, 220 plastic bottle acoustic reflectors). A total of 2157 specimens across 26 different species were identified in the catch. The most frequently species by occurrence and number were *Euthynnus affinis* (1480 specimens across 294 sets), *Thunnus albacares* (177 specimens across 95 sets), *Coryphaena hippurus* (123 specimens across 114 sets), *Scomberomorus commerson* (78 specimens across 60 sets), and *Istiophorus platypterus* (70 specimens across 70 sets). Across the 800 sets where target species catch could be monitored 236 (29.5%) had no catch at all. Given the overall complexity of the catch we focussed our assessment on the total catch across tuna species (1707 individuals found across 350 sets, including 50 individuals of *Katsuwonus pelamis* in 11 sets). The occurrence of tunas in the catch was not significantly affected by glass bottle pingers (GLMM, $Z = -0.414$, $p = 0.679$) or plastic bottle acoustic reflectors (GLMM, $Z = -1.24$,

Table 2

Sample size, small cetacean catch, bycatch rate, bycatch and target catch statistics from bycatch mitigation trials in Brazil, Peru and Zanzibar (Tanzania).

	No sets	Small cetacean catch	Bycatch rate	Small cetacean bycatch	Target catch
Brazil					
Control	57	4	0.070		
Plastic bottle	48	0	0	$p = 0.075\downarrow$	$p = 0.035\uparrow$
Peru					
Control	241	28	0.116		
Plastic bottle	95	10	0.105	$p = 0.861$	$p > 0.05$
Glass	120	16	0.150	$p = 0.098$	$p > 0.05$
Zanzibar					
Control	401	0	0		
Plastic bottle	312	0	0		$p < 0.001\uparrow$
Glass	394	0	0		$p > 0.05$

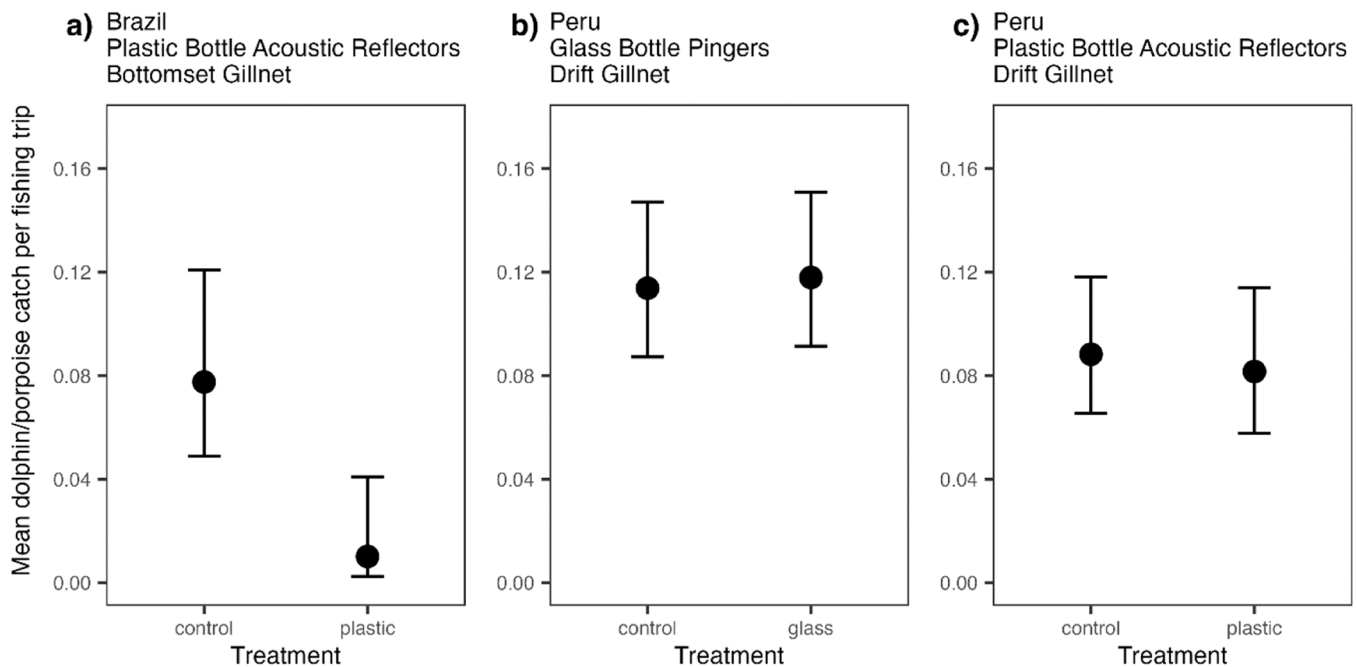


Fig. 4. Bycatch rates ($\pm$ SE) of dolphin and porpoise in up-cycled glass bottle pingers and plastic bottle acoustic reflectors trials. a) plastic bottle acoustic reflectors in the bottom-set trammel net fishery of Torres and Passo de Torres, Brazil. b) plastic bottle acoustic reflectors in the surface-set driftnet fishery of Salaverry, Peru. c) glass bottle pingers in the surface-set driftnet fishery of Salaverry, Peru.

$p = 0.214$). However, the number of tunas caught when a catch event occurred was significantly higher in nets with plastic bottle acoustic reflectors than control nets (GLMM, $Z = 5.63$, $p < 0.001$), there was no effect in nets with glass bottle pingers (GLMM, $Z = 1.50$, $p = 0.133$). Across all trials, irrespective of the statistically detected changes outlined above, fishers did not declare any perceived changes in their target fish catches.

Appendix A presents detailed statistics of non-cetacean species catch in Peru and Zanzibar. Appendix B presents the full model outputs from the statistical analyses.

4. Discussion

We tested potential low-cost dolphin bycatch mitigation devices developed from upcycled glass and plastic drink bottles. Our results suggest that the up-cycled plastic bottle acoustic reflectors may be an effective low-cost mitigation tool to reduce dolphin bycatch in bottom-set trammelnets. However, we found no evidence for their effectiveness in surface-set driftnet fisheries, potentially a result of the more dynamic acoustic environment near the water surface. This study indicates that it may be possible to develop cost-effective bycatch mitigation solutions that reduce dolphin bycatch without affecting target catch and may have positive effect on some target species catch. This would address and mitigate the two major barriers (cost and effect on target catch) for fishers to implement bycatch reduction methodologies. We encourage further tests with plastic bottle acoustic reflectors in other fisheries and areas to evaluate if the methodology may have wider application for bottom-set gillnet fisheries to mitigate dolphin and other toothed whale bycatch.

The results from Brazil may be explained by the increased acoustic backscatter by the plastic bottles in the nets providing echolocating dolphins with improved ability to detect bottom-set gillnets and to avoid entanglement. In contrast, the results from the trials in the driftnets in Peru did not reduce dolphin and porpoise bycatch using either glass bottle pingers or plastic bottle reflectors. It is possible that the ambient noise levels near the surface-set driftnets in Peru masked the sound from the glass bottle pingers and the acoustic backscatter from the plastic

bottles and reduced the efficacy of the bottles to alert dolphins and porpoises to the presence of the net. The lower ambient light levels where bottom-set trammel nets (and other gillnets) are used compared to surface-set driftnets may also explain why the plastic bottles reduced dolphin bycatch in bottom-set nets as dolphins would rely more on echolocation in low light environments and be more likely to detect the bottles in the nets.

In general, the occurrence of target fish species catches was not affected by either glass or plastic bottle treatment. However, catch numbers increased in nets with plastic bottles for tuna catch in Zanzibar. It is possible that the plastic bottles in the nets reflected light sources in the marine environment and acted as potential lures attracting fishes to the driftnets. These results were positive to the fishers as potential negative impact from bycatch mitigation methods on target catch species is one of the main barriers to fishers for implementing changes in their fisheries (Richardson et al., 2005; Mangel et al., 2013; Berninsone et al., 2020). The glass bottle pingers resulted in contrasting results for the presence of ray and shark catches in Peru where ray catch occurrence was negatively affected and shark catch positively affected with no subsequent effects on level of catches given presence. However, if only catches of smooth hammerhead sharks (*Sphyrna zygaena*), which made up 92% of shark catches by number, were considered then there was no difference in shark catch between nets with glass bottle pingers and control nets. These contrasting results suggest that glass bottle pingers may affect the likelihood of some other shark species being caught. The shark species caught in the fishery off Peru included *Galeorhinus galeus*, *Isurus oxyrinchus*, *Alopias vulpinus* and *Carcharinus brachyurus* which are listed as Threatened (Critically Endangered, Endangered or Vulnerable) with decreasing populations trends by the International Union for Conservation of Nature Red List (www.iucnredlist.org) and an increased level of shark catch may therefore have negative effects both on the species and wider ecosystem.

The dolphin bycatch rates in all three trials were lower in the control sets compared to available data from prior investigations that were used in sample size calculations (Zanzibar: 0/0.02, Peru 0.116/0.34, and Brazil 0.070/0.28). The effect of this was that larger sample sizes would have been needed to demonstrate the 50%, 75% and 80% reduction in

dolphin bycatch with 80% power at the 5% significance level used in the calculations. The lower bycatch rate was particularly evident in Zanzibar where there was no dolphin bycatch in any of the control or treatment sets. Declining dolphin populations may be one reason for the lower bycatch rates, particularly in Brazil and Zanzibar where the bycatch occur in areas with relatively small dolphin populations and where previous studies have indicated that the bycatch levels are likely unsustainable (Amir et al., 2005; Sharpe and Berggren, 2019; Sucunza et al., 2023). Access to current estimates of bycatch rates is imperative for planning future trials to ensure sufficient sample sizes and statistical power are used in the trials to ensure evaluation of the tested methodology is meaningful. The lower dolphin bycatch rate in the control sets in Brazil can explain why this trial was not significant at the 5% significance level.

Further trials are under way in Brazil in the same fishery to determine if the initial results presented here represent a long-term solution to mitigate bycatch of *Pontoporia blainvillei* using plastic bottle acoustic reflectors throughout their range in coastal waters of western South Atlantic. Bottom-set trammel and other gillnets are extensively used in Brazil and neighbouring countries and there is an urgent need to find low-cost solutions to reduce bycatch to mitigate the current threat of extinction to the species listed as Vulnerable by the IUCN Red List (Secchi et al., 2021).

Participating fishers in all three areas did not perceive any negative impacts of the bottles on their fishing practice or catches. All three fisheries in the trials are small-scale, setting and hauling the nets by hand. There were some initial breakages of glass bottles in Peru and Zanzibar, but these were mitigated by adjusting hauling speeds when net sections with bottles approached the boat. Before trials with the glass and/or plastic bottles are tested in fisheries using hydraulic net haulers it may be necessary to attach/remove bottles before they go through the hauler.

Depending on where in the net and at what depth nets are deployed in the water column, the plastic bottles' air volume will be compressed following the deal gas equation: $pV=nRT$ (where p , V and T are the pressure, volume and temperature, respectively; n is the amount of substance; and R is the ideal gas constant). Therefore, at 10 m depth the pressure doubles from 1 atm to 2 atm and hence the volume air reduces by 0.5 and the surface area (= target strength) reduces by $0.5^2/3 = 0.63$ or 2 dB. This neglects the shape/rigidity of the bottle so in practice the reduction may be smaller than this. The compression of the bottles and how that may affect their acoustic reflection need further investigation and should be considered in any future trials. This did not appear to affect the acoustic backscatter of the bottles in the trials in Brazil where nets were set at an average depth of 22 m (± 3 m).

The trials with the glass bottle pingers did not result in a reduction of dolphin bycatch in the fisheries where the trials were conducted. However, this should not prevent trialling the methodology in other gillnet fisheries and/or in other areas. Given the acoustic properties of the glass bottle pingers it may prove successful to reduce bycatch of the same, as investigated in this study, or other cetacean species in other gillnet fisheries and areas. The glass bottles on the nets in the Peru were attached every 93 m on average (± 5 m) on the headrope of the driftnet and only three of the total 18 dolphin bycatches occurred close to bottles in the nets (at 6, 9 and 18 m from the nearest bottle, respectively), indicating that any future trials with the glass bottles should consider a closer spacing between bottles.

Using plastic bottles in the marine environment requires careful attention to prevent any loss that contributes to pollution. By securing the plastic bottles to the nets with efficient knots no bottles were lost during the trials conducted. Given that we upcycled and used available empty drink bottles this possibly contributed to an overall reduction in bottle pollution.

There are other potential low-cost mitigation methods that should be considered to reduce dolphin bycatch in gillnet fisheries (see e.g., Hamilton and Baker, 2019; Lucas and Berggren, 2023) including

sub-surface setting of surface driftnets which have been tested with successful results (Kiszka et al., 2021).

5. Conclusions

The result from the trials in Brazil indicated that plastic bottle acoustic reflectors used in bottom-set trammel nets may reduce dolphin bycatch which represent an important and promising result for finding low-cost method to address cetacean bycatch in gillnet fisheries. Further trials are needed to confirm these preliminary results. Trials conducted in the driftnet fisheries off Peru and Zanzibar did not show a reduction in dolphin bycatch using either glass bottle pingers or plastic bottle reflectors indicating that these methods may not be successful to reduce dolphin bycatch in surface-set driftnets. The trials indicated that the occurrence of target fish species was not affected by having glass bottle pingers or plastic bottle acoustic reflectors, however, catch levels of some target species increased when using plastic bottle acoustic reflectors.

Ethical statement

This study was approved by the Newcastle University Animal Welfare Ethical Review Body (AWERB, Project ID No: 727).

CRedit authorship contribution statement

Andrew Temple: Writing – review & editing, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gabriel Larre:** Writing – review & editing, Resources. **Jeff Neasham:** Writing – review & editing, Resources. **Per Berggren:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jiddawi Narriman:** Writing – review & editing, Resources. **Matt Sharpe:** Writing – review & editing, Resources, Methodology, Investigation, Data curation, Conceptualization. **Mangel Jeffrey:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Joanna Alfaro-Shigueto:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. presents detailed statistics of non-cetacean species catch in Peru and Zanzibar

Appendix A

Catch statistics of non-cetacean species during bycatch mitigation trials in Peru and Zanzibar (Tanzania)

Country	Peru				Zanzibar**		
Treatment	Glass	Control	Plastic	Control	Glass	Plastic	Control
Number sets	120	120	95	121	394	312	401
Species	Number specimens						
<i>Alopias sp</i>	57	112	30	232	1	0	0
<i>Carcharinus brachyurus</i>	18	6	21	36	0	0	0
<i>Carcharinus falciformis</i>	3	0	0	0	6	1	6
<i>Carcharinus limbatus</i>	3	0	0	0	0	0	0
<i>Carcharhinus sp</i>	2	0	1	3	0	0	0
<i>Galeorhinus galeus</i>	12	11	0	0	0	0	0
<i>Isurus oxyrinchus</i>	2	1	4	34	0	0	0
<i>Notorynchus cepedianus</i>	0	1	0	0	0	0	0
<i>Prionace glauca</i>	122	197	447	453	0	0	0
<i>Sphyrna zygaena</i>	3379	3617	4860	2986	0	0	0
<i>Triakis maculata</i>	0	13	0	0	0	0	0
<i>Mobula sp</i>	13	0	142	0	1	1	1
<i>Myliobatis sp</i>	292	1274	154	356	1	0	0
<i>C. hippurus</i>	649	179	592	410	62	53	26
<i>Sporothrix chiliensis</i>	372*	0	0	0	32	22	23
<i>Xiphias gladius</i>	2	0	0	1	0	1	1
<i>Istiophorus platypterus</i>	0	0	0	0	0	0	0
<i>Euthynnus affinis</i>	0	0	0	0	428	416	779
<i>Thunnus albacares</i>	0	0	0	0	81	63	69
<i>Scomberomorus commerson</i>	0	0	0	0	34	30	27
<i>Katsuwonus pelamis</i>	0	0	0	0	25	18	1
<i>Carangidae sp</i>	0	0	0	0	8	57	12
<i>Makaira indica</i>	0	0	0	0	4	1	4
<i>Rachycentron canadum</i>	0	0	0	0	16	13	6
<i>Belonidae sp</i>	0	0	0	0	3	6	4
<i>Diodon hystrix</i>	0	0	0	0	1	7	0
<i>Lobotes surinamensis</i>	0	0	0	0	8	5	11
<i>Caretta caretta</i>	1	0	0	0	0	0	0
<i>Caretta mydas</i>	23	16	8	12	0	0	0
<i>Dermochelys coriacea</i>	0	1	1	1	0	0	0
<i>Lepidochelys olivacea</i>	1	2	0	1	0	0	0
<i>Eretmochelys imbricata</i>	0	0	1	0	0	0	0

* From 2 sets only.

** An additional eight species with $n < 5$ were recorded.

Appendix B. presents the full model outputs from the statistical analyses

Appendix B. Model outputs of statistical tests investigating potential effects on catch target and bycatch species in trials with upcycled glass and plastic bottles in driftnet fisheries in Peru and Zanzibar (Tanzania), and a trammel net fishery in Brazil.

1. Dolphin Bycatch

Table 1

Brazil – Penalised Logistic Regression (Firth's Method)

Parameter	Coef	SE	95% CI (Lower)	95% CI (Upper)	χ^2	p
Intercept	-2.476	0.491	-3.594	-1.623	48.756	< 0.001 ***
treatment [plastic]	-2.099	1.504	-6.995	0.178	3.168	0.075

Coefficients estimated by penalised ML (Profile penalized log-likelihood CIs).

Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Formula: $\text{dolphins} \sim \text{treatment} \mid n = 105 \mid \text{LRT } \chi^2(1) = 3.168, p = 0.0751 \mid \text{Wald } \chi^2(1) = 35.80, p = 2.19 \times 10^{-9}$

Table 2

Peru – Binomial GLMM with Effort Offset (logit link)

Parameter	Estimate	SE	z	p
(a) Glass treatment AIC = 178.0 BIC = 184.9 logLik = -87.0 df.resid = 238				
Intercept	-6.030	0.295	-20.448	< 0.001 ***

(continued on next page)

Table 2 (continued)

Parameter	Estimate	SE	z	p
treatment [glass]	0.040	0.410	0.098	0.922
(b) Plastic treatment AIC = 135.7 BIC = 142.5 logLik = -65.9 df.resid = 214				
Intercept	-6.515	0.324	-20.122	< 0.001 ***
treatment [plastic]	-0.086	0.492	-0.175	0.861

Two separate models fitted for glass and plastic treatment contrasts. $p = 0$ denotes $p < 2 \times 10^{-16}$. Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Formula: $\text{dolphins} \sim \text{treatment} + \text{offset}(\log(\text{power_km_hrs}))$ | Family: binomial (logit)

Zanzibar – Dolphin Bycatch

No dolphin bycatch events were recorded at the Zanzibar site ($n = 0$ captures). Model fitting was not performed.

2. Fish Catch

Table 3

Brazil – Fish Catch Weight (Gamma GLM, log link)

Parameter	Estimate	SE	z	p
Intercept	-1.430	0.424	-3.368	< 0.001 ***
treatment [plastic]	0.266	0.126	2.106	0.035 *
depth_m	0.077	0.020	3.785	< 0.001 ***

Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Formula: $\text{fish_catch_kg} \sim \text{treatment} + \text{depth_m} + \text{offset}(\log(\text{power_km_hrs}))$ | AIC = 1174.5 | BIC = 1185.1 | logLik = -583.3 | df.resid = 101 | Dispersion $\sigma^2 = 0.408$

Table 4

Peru (Glass) – Sharks: Zero-Inflated Truncated Negative Binomial

Parameter	Estimate	SE	z	p
Conditional Model				
Intercept	-3.090	0.606	-5.098	< 0.001 ***
treatment [glass]	0.268	0.244	1.100	0.272
Captain [JRU]	-0.581	0.307	-1.890	0.059.
Captain [MHF]	0.172	0.552	0.312	0.755
Captain [RBH]	0.725	0.305	2.377	0.017 *
Target [Fish]	0.304	0.673	0.452	0.651
Target [Mix]	2.937	0.698	4.205	< 0.001 ***
Target [Ray]	0.667	1.503	0.444	0.657
Target [Shark]	2.188	0.529	4.133	< 0.001 ***
Zero-Inflation Model				
Intercept	0.392	0.690	0.569	0.570
treatment [glass]	-1.469	0.571	-2.572	0.010 *
Captain [JRU]	-1.976	0.813	-2.432	0.015 *
Captain [MHF]	-0.295	0.719	-0.411	0.681
Captain [RBH]	-2.659	0.721	-3.688	< 0.001 ***
Target [Fish]	-16.111	3194.549	-0.005	0.996
Target [Mix]	-1.412	0.956	-1.477	0.140
Target [Ray]	0.994	1.314	0.757	0.449
Target [Shark]	-0.684	0.795	-0.860	0.390

Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Formula (count): $\text{sharks} \sim \text{treatment} + \text{Captain} + \text{Target} + \text{offset}(\log(\text{power_km_hrs}))$ | Zero-inflation: $\sim$. | AIC = 1954.4 | BIC = 2020.6 | logLik = -958.2 | df.resid = 221 | Dispersion $\theta = 0.506$

Table 5
Peru (Glass) – Rays: Zero-Inflated Truncated Negative Binomial

Parameter	Estimate	SE	z	p
Conditional Model				
Intercept	0.204	0.268	0.761	0.447
treatment [glass]	0.076	0.552	0.138	0.890
Captain [JRU]	-3.358	1.373	-2.445	0.015 *
Captain [MHF]	-1.503	0.739	-2.035	0.042 *
Captain [RBH]	-2.514	1.284	-1.959	0.050.
Zero-Inflation Model				
Intercept	-0.123	0.324	-0.381	0.703
treatment [glass]	1.592	0.523	3.047	0.002 **
Captain [JRU]	2.989	1.054	2.837	0.005 **
Captain [MHF]	1.423	0.727	1.956	0.051.
Captain [RBH]	4.335	1.048	4.137	< 0.001 ***

Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Formula (count): $\text{rays} \sim \text{treatment} + \text{Captain} + \text{offset}(\log(\text{power_km_hrs}))$ | Zero-inflation: $\sim$. | AIC = 429.0 | BIC = 467.3 | $\log\text{Lik} = -203.5$ | $\text{df.resid} = 229$ | Dispersion $\theta = 0.713$

Table 6
Peru (Plastic) – Sharks: Zero-Inflated Truncated Negative Binomial

Parameter	Estimate	SE	z	p
Conditional Model				
Intercept	-2.433	0.463	-5.261	< 0.001 ***
treatment [plastic]	-0.060	0.305	-0.198	0.843
Captain [MHF]	-2.219	1.007	-2.203	0.028 *
Captain [RBH]	0.603	0.239	2.519	0.012 *
Target [Mix]	2.064	0.494	4.179	< 0.001 ***
Target [Shark]	0.260	0.501	0.520	0.603
Zero-Inflation Model				
Intercept	-1.319	0.750	-1.758	0.079.
treatment [plastic]	0.578	0.802	0.720	0.471
Captain [MHF]	2.603	0.904	2.878	0.004 **
Captain [RBH]	0.903	0.822	1.100	0.272
Target [Mix]	-3.603	1.020	-3.533	< 0.001 ***
Target [Shark]	-2.803	0.914	-3.066	0.002 **

Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Formula (count): $\text{sharks} \sim \text{treatment} + \text{Captain} + \text{Target} + \text{offset}(\log(\text{power_km_hrs}))$ | Zero-inflation: $\sim$. | AIC = 1766.3 | BIC = 1810.2 | $\log\text{Lik} = -870.2$ | $\text{df.resid} = 203$ | Dispersion $\theta = 0.35$

Table 7
Peru (Plastic) – Rays: Zero-Inflated Truncated Negative Binomial

Parameter	Estimate	SE	z	p
Conditional Model				
Intercept	-0.386	0.316	-1.220	0.222
treatment [plastic]	-0.016	0.345	-0.046	0.963
Captain [MHF]	-2.259	0.352	-6.415	< 0.001 ***
Captain [RBH]	-1.486	0.452	-3.285	0.001 **
Zero-Inflation Model				
Intercept	1.893	0.400	4.733	< 0.001 ***
treatment [plastic]	0.463	0.499	0.929	0.353
Captain [MHF]	-4.508	0.819	-5.506	< 0.001 ***
Captain [RBH]	0.411	0.507	0.811	0.417

Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Formula (count): $\text{rays} \sim \text{treatment} + \text{Captain} + \text{offset}(\log(\text{power_km_hrs}))$ | Zero-inflation: $\sim$. | AIC = 388.0 | BIC = 418.4 | logLik = -185.0 | df.resid = 207 | Dispersion $\theta = 1.47$

Table 8

Zanzibar (Glass) – Tuna: Zero-Inflated Truncated Negative Binomial

Parameter	Estimate	SE	z	p
Conditional Model				
Intercept	-18.244	2630.266	-0.007	0.994
treatment [Plastic]	1.661	0.295	5.626	< 0.001 ***
treatment [Glass]	0.407	0.271	1.503	0.133
Month	-0.760	0.185	-4.110	< 0.001 ***
Zero-Inflation Model				
Intercept	-1.078	0.223	-4.831	< 0.001 ***
treatment [Plastic]	-0.229	0.185	-1.242	0.214
treatment [Glass]	-0.072	0.175	-0.414	0.679
Month	0.683	0.096	7.111	< 0.001 ***

Reference level for treatment is the control (no gear modification). Dispersion $\theta \approx 0$ indicates near-Poisson behaviour.

Significance codes: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Formula (count): $\text{Total_Tuna} \sim \text{treatment} + \text{Month} + \text{offset}(\log(\text{power_km_hrs}))$ | Zero-inflation: $\sim$. | AIC = 2548.4 | BIC = 2590.6 | logLik = -1265.2 | df.resid = 791 | Dispersion $\theta \approx 0$

Data availability

Data will be made available on request.

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