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# Do by-catch reduction devices in longline fisheries reduce capture of sharks and rays? A global meta-analysis

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## Abstract

By-catch in marine fisheries, particularly those using pelagic and demersal longlines, is a major driver of declines in abundance of sharks and rays around the world. A wide variety of by-catch reduction devices (BRDs), that is, modified gears designed to reduce incidental captures of a variety of marine species while maintaining target catch rates, have been proposed, but the extent to which BRDs actually reduce the risk of catching sharks and rays remains unclear. We performed a meta-analysis of 27 publications that reported the capture of sharks and rays and, in some cases, of targeted teleosts in longline gear deployed with and without BRDs. The risk of shark and ray capture differed between types of BRDs, but only one BRD type, longlines raised off the bottom, reduced by-catch significantly. Circle hooks did not reduce the risk of capturing sharks and rays but might improve discard survival and are inexpensive, which might make them effective in reducing the detrimental effects of longlining on these species. In addition to being generally ineffective, some devices, such as electropositive and magnetic repellents, are expensive and have inherent construction drawbacks that are likely to make them unsuitable for commercial use. Overall, most BRDs did not affect the likelihood of catching targeted teleosts, but a substantial number of studies did not adequately assess target catch. We identified two poorly studied classes of BRD gear (i.e. raised demersal longlines, and monofilament nylon leaders), which represent promising directions for future research.

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## Introduction

By-catch, or the unintentional catch of non-target species occurring in fisheries (Kennelly 2007), is a major source of mortality for shark and ray populations around the world (Gilman *et al.* 2008; Petersen *et al.* 2009). Nearly a third of currently assessed sharks, skates and rays have been designated as threatened or near-threatened by the International Union for Conservation of Nature (IUCN 2012), mainly due to exploitation, either targeted or incidental, by industrial fisheries (Stevens *et al.* 2000; Molina and Cooke 2012). Most sharks and rays are slow-growing, achieve sexual maturity at a late age and produce few offspring, making their populations especially sensitive to fishing pressure (Dulvy *et al.* 2008; García *et al.* 2008; Hutchings *et al.* 2012).

Of all industrial fishing methods, longlining presents one of the highest risks to sharks and rays (Watson and Kerstetter 2006; Gilman *et al.* 2008; Molina and Cooke 2012). Interactions between sharks or rays and longline fishing gear can also decrease fishing profitability. Sharks often consume targeted fishes caught on hooks (Gilman *et al.* 2007), and hooked sharks and rays can damage gear, block the hooks from catching more valuable species and increase the handling time of gear upon retrieval (Gilman *et al.* 2008). The costs imposed by these interactions are substantial, prompting calls for methods to repel sharks and rays from deployed fishing gear (Molina and Cooke 2012).

A potential solution to the problem of by-catch is the use of by-catch reduction devices (BRDs), or technologies that prevent the capture, or facilitate escape, of non-target species from fishing gear (FAO 2002). BRDs represent physical alterations to fishing gear and are distinct from changes in fishing technique (e.g. changes to soak duration or timing), which use existing gear in novel ways to influence capture rates of target and non-target species (Ward and Hindmarsh 2007). There is an ongoing global effort to develop and implement BRDs to reduce by-catch across all fisheries (Cox *et al.* 2007). BRDs are an attractive solution because, unlike area closures and other restrictive management measures (e.g. Grantham *et al.* 2008), they offer fishers the opportunity to maintain most of their fishing activities with little cost, other than that of purchasing the gear modification. The design and promotion of BRD technology are therefore widespread, including through a high-profile international competition to encourage the development of novel BRDs (World Wildlife Fund 2011).

Devices that reduce shark and ray by-catch in longlines vary widely in design, ranging from electric and magnetic repellents to modified hooks. While qualitative reviews of the costs and benefits of the commonest types of BRDs have been conducted (Swimmer *et al.* 2008; Molina and Cooke 2012), a quantitative assessment comparing the effectiveness of all existing BRD approaches is currently lacking. Here, we conducted a meta-analysis of peer-reviewed and grey literature to assess the effectiveness of existing technology at reducing the risk of catching sharks and rays on longlines. We first asked whether such BRD technology works in general. We combined all studies, irrespective of BRD type or species, to generate the first estimate of the overall magnitude of change in shark and ray catches caused by BRD technology compared with conventional longline gear. We then examined the effectiveness of different types of BRDs. We generally did not focus on species-specific effects because longlining gear typically captures a range of shark and ray species, thus BRD effectiveness should arguably be measured across all species captured. However, we did consider separately the results of studies focusing on a single shark or ray species and asked whether BRD effectiveness varied in relation to the level of endangerment of these species. Where possible, we also compared the effect of BRD on shark and ray capture with its effect on the capture of targeted teleost fishes, to highlight gears that manage to reduce by-catch while maintaining the capture of target species. We conclude by identifying promising avenues for future research and development.

## Methods

We conducted a meta-analysis to generate a quantitative measure of the overall effectiveness of by-catch reduction technology applied to longline fishing gear (Harrison 2011). We identified publications that reported the numbers of sharks and rays caught in fishing gears equipped with BRDs and without BRDs and deployed in the field. We searched three main databases: Bycatch.org, Web of Science and the Aquatic Sciences and Fisheries Abstracts Database Guide (ASFA). We also considered papers cited in major review documents and those which we encountered opportunistically (i.e. new papers not yet indexed in the above databases). We followed PRISMA best-practice protocols for conducting this review (Moher *et al.* 2009, Appendix S1).

Our criteria for inclusion were threefold. First, the paper had to compare experimentally the catch composition of two or more gear types (unmodified 'control' gear vs. some type of BRD). Second, the BRD had to be applied to a hook-based fishing gear (i.e. pelagic longline, demersal longline or hook-and-line), which was similar to that used in commercial fisheries. Third, the experiment had to have been conducted in the field, and not in a laboratory environment. The BRDs did not have to be designed specifically to exclude sharks and rays – they could have been built primarily to protect other species; however, we included them if their effect on shark and ray catch was adequately measured and reported. We included all peer-reviewed literature and government publications that met these three criteria (Fig. 1). Our search terms (see online supplement) were intentionally broad to ensure the identification of as many publications as possible.

We used relative risk (RR) as our measure of effect size (Zhang and Yu 1998). To do so, we recorded from each study: the number of control hooks and the number of BRD-equipped hooks deployed, the number of hooks of each type which caught a shark or ray and the number of hooks of each type which caught a targeted teleost fish. Relative risk to sharks and rays was calculated as $RR = (a/n_1)/(b/n_2)$, where a and b were the numbers of hooks equipped with a BRD or not, respectively, that caught a shark or ray, and $n_1$ and $n_2$ were the total numbers of hooks employed in the study with and without a BRD, respectively. We also calculated relative risk to targeted fishes, where a and b were the numbers of hooks equipped with a BRD or not, respectively, that

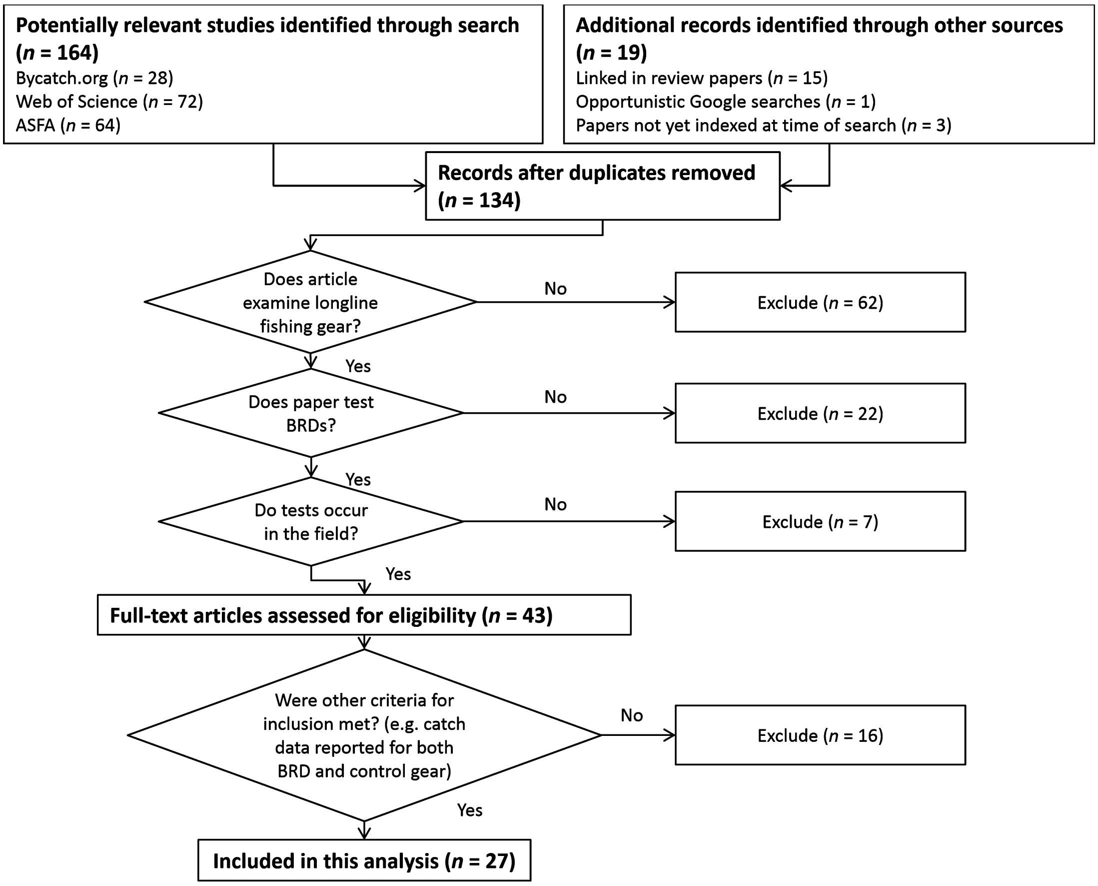

**Figure 1** Flowchart outlining criteria for inclusion of papers into our meta-analysis.

caught a teleost fish. Relative risk is superior to the odds ratio as a measure of effect size for data where occurrence rates are above 10%, which was the case for our data (Zhang and Yu 1998; Koricheva *et al.* 2013). Relative risk effect sizes are statistically significant if the 95% C.I. of the model coefficient does not span one. The log of the relative risk was used in the analyses because it normalizes the results and makes the coefficients symmetrical around zero (Viechtbauer 2010).

We identified nine broad types of BRDs, which we describe briefly below. (i) *Circle hooks* have a rounded shape and are designed to become lodged in the jaw of fish, rather than in the internal organs as can happen with traditional J-shaped hooks (Godin *et al.* 2012). Circle hooks were designed primarily to reduce capture of sea turtles and to reduce gut-hooking of fishes, which promotes post-release survival, but these hooks have also been assessed for their ability to reduce shark and ray by-catch (Godin *et al.* 2012). (ii) *Appendage hooks* are circle hooks which contain an extension, or 'appendage', which is designed to increase the hook's width and make it more difficult for undersized animals to ingest (Swimmer *et al.* 2011). (iii) *Electropositive repellents* are created from alloys that oxidize in salt water, generating an electric field (Kaimmer and Stoner 2008). Electropositive BRDs can take the form of a small ingot placed above the hook (e.g. Kaimmer and Stoner 2008) or can be woven into the hooks themselves (e.g. O'Connell *et al.* 2014). (iv) *Magnetic repellents* are similar to electropositive BRDs, but are built using permanent magnets and produce a magnetic rather than an electrical field. Both electric and magnetic fields are detectable by ampullae of Lorenzini, which are electroreceptors that trigger avoidance in sharks and rays when overstimulated (Murray 1960). (v) *Combined* repellents, known as SMART™ hooks, include both electropositive and magnetic repellents integrated into the same hook (O'Connell *et al.* 2014). (vi) *Changes to bait colour* involve dyeing bait blue to reduce visibility to seabirds, and this method has been assessed for its ability to reduce by-catch of sharks and rays as well (Yokota *et al.* 2006). (vii) *Breakable monofilament nylon leaders* replace wire leaders (i.e. the lines which connect the hooks to the main longline) with less durable nylon, which sharks and rays can bite off, thus preventing their capture (Ward *et al.* 2008). (viii) *Tarred multifilament nylon leaders* are thicker and darker than monofilament nylon leaders, and therefore may be easier for fish of all species to see and avoid (Stone and Dixon 2001). (ix) *Raised lines* involve the use of floats to raise the demersal longline off the bottom to avoid capture of bottom-dwelling shark and ray species (Afonso *et al.* 2011).

### Statistical analysis

By-catch affects a wide range of shark and ray species, so an ideal BRD should be effective at reducing by-catch across species. We therefore performed our meta-analysis on shark and ray catch data pooled across all reported species, as the outcome of interest was the overall effect of BRDs rather than their species-specific effects. When publications reported the results of multiple independent field studies, we calculated a separate effect size for each study. In addition, when a study focused on a single species of shark or ray, we recorded the IUCN Red List status of that species (IUCN 2012). For most types of BRD, the comparison (control vs. modified) was clear and unambiguous. However, for magnetic and electropositive BRDs, a 'procedural control' was usually employed, where a comparison was made between hooks with an inert metal attached (procedural control), and hooks with a BRD attached (e.g. Kaimmer and Stoner 2008; Brill *et al.* 2009; O'Connell *et al.* 2011; Hutchinson *et al.* 2012; Godin *et al.* 2013). In the two magnet and electropositive BRD studies where procedural controls were not used, we calculated the effect size by comparing the BRD-equipped catch with standard controls (Tallack and Mandelman 2009; Robbins *et al.* 2011).

We conducted two analyses, each applied to the risk of capture of sharks and rays and then of targeted teleosts. First, we used a random-effects model to generate a grand overall effect size across all types of BRDs on shark and ray by-catch (Viechtbauer 2010). We employed random-effects modelling because we anticipated substantial heterogeneity among studies, owing to differences among species, locations and unrecorded BRD details (e.g. different-sized hooks, bait types, etc.). In addition, we sought to make an inference about the overall effect of BRDs that was not limited to the studies included in the analysis (Worm and Myers 2003). Second, we constructed a mixed-effects model, which incorporated BRD type as a moderator, to compare the effectiveness of each class of BRD at reducing catch of sharks and rays

(Viechtbauer 2010). We measured heterogeneity for both sets of models using a restricted maximum-likelihood estimator ($\tau^2$) (Viechtbauer 2005), instead of $I^2$, which is another common measure of the proportion of variability due to heterogeneity. However, as the sample sizes in longline studies are extremely large, $I^2$ would likely overestimate heterogeneity (Rücker *et al.* 2008). We tested the significance of $\tau^2$ using Cochran's Q test (Hedges and Olkin 1985). For each mixed-effects model, we conducted an omnibus test to test whether model coefficients were equivalent across BRD types (Hedges and Pigott 2004; Viechtbauer 2010). We conducted all analyses using the Metafor package in R (Viechtbauer 2010; R Development Core Team 2011).

## Results

Our literature search yielded 183 publications, and after duplicates and non-relevant publications were removed, 27 remained for incorporation into the present meta-analysis (Fig. 1, see online supplement). These 27 publications yielded 44 separate studies that met our criteria; a total of 28 studies also reported teleost catch data.

Overall, the use of BRDs did not significantly lower the risk of capturing sharks and rays ($\exp(\widehat{\mathrm{RR}}) = 0.881$, 95% CI = 0.761 to 1.020; Fig. 2) or targeted teleosts ($\exp(\widehat{\mathrm{RR}}) = 0.934$, 95% CI = 0.836 to 1.043; Fig. 2). There was substantial heterogeneity among studies in risk to sharks and rays ($\tau^2 \pm 1$ SE = $0.221 \pm 0.053$, Q = 1840.5, df = 43, $P < 0.0001$). When BRD type was incorporated as a moderator, there remained significant residual heterogeneity among studies ($\tau^2 \pm 1$ SE = $0.185 \pm 0.050$, $Q_E = 1366.1$, df = 35, $P < 0.0001$). For teleosts, there was also significant heterogeneity in the overall model ($\tau^2 \pm 1$ SE = $0.068 \pm 0.023$, Q = 574.8, df = 27, $P < 0.0001$), and residual heterogeneity was significant but smaller with BRD type included as a moderator ($\tau^2 \pm 1$ SE = 0.045

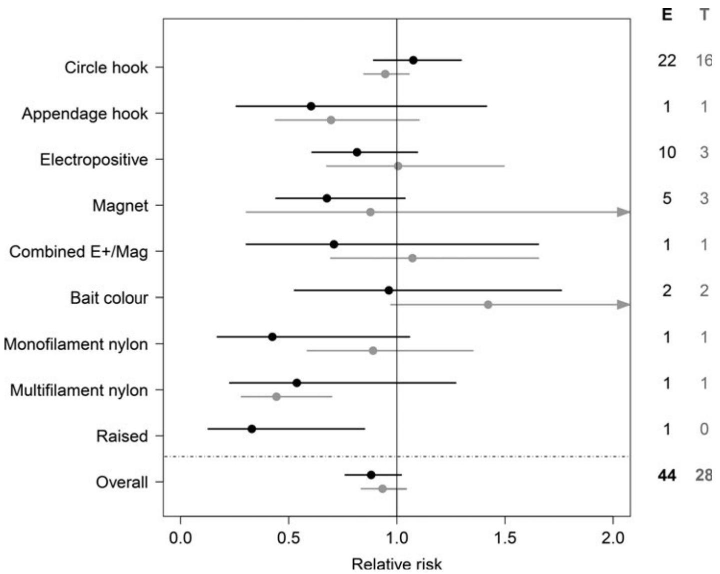

**Figure 2** Effect of various types of by-catch reduction devices (BRD) on the risk of capturing non-targeted elasmobranchs (black) and targeted teleost fishes (grey). Points indicate modelled effect size as determined by random-effects modelling (for overall effect sizes) and by mixed-effects models for each BRD class. Bars represent 95% confidence intervals. Relative risk <1 indicates a lower risk of capture on BRD-equipped hooks relative to control gear, while >1 represents increased risk of capture. Numbers on the right represent the number of studies with elasmobranch data (E) and the numbers that also contained teleost data (T). Studies included in each class of BRD: Circle hooks: Bolten and Bjorndal (2005); Watson *et al.* (2005); Ingram *et al.* (2005); Yokota *et al.* (2006); Kim *et al.* (2007, 2006); Promjinda *et al.* (2008); Carruthers *et al.* (2009); Ward *et al.* (2009); Sales *et al.* (2010); Piovano *et al.* (2010); Afonso *et al.* (2011); Curran and Bigelow (2011); Pacheco *et al.* (2011); Domingo *et al.* (2012. Appendage hook: Swimmer *et al.* (2011). Electropositive: Kaimmer and Stoner (2008); Brill *et al.* (2009); Tallack and Mandelman (2009); Robbins *et al.* (2011); Hutchinson *et al.* (2012); Godin *et al.* (2013). Magnet: O'Connell *et al.* (2011); Robbins *et al.* (2011). Combined: O'Connell *et al.* (2014). Bait colour: Yokota *et al.* (2009). Monofilament nylon: Ward *et al.* (2008). Multifilament nylon: Stone and Dixon (2001). Raised: Afonso *et al.* (2011).

± 0.018, $Q = 480.5$, df = 20, $P < 0.0001$). The omnibus tests showed that BRD type had a significant effect on relative risk of both shark and ray capture ($Q_M = 18.3$, df = 9, $P = 0.032$) and teleost capture ($Q_M = 19.4$, df = 8, $P = 0.013$). The raised line device was the only BRD type that significantly reduced shark and ray catch (i.e. the 95% CI does not encompass 1, $\exp(\hat{\beta}_9) = 0.329$, 95% CI = 0.128 to 0.850). Furthermore, only multifilament nylon leaders reduced the relative risk of teleost capture ($\exp(\hat{\beta}_8) = 0.443$, 95% CI = 0.281 to 0.698), while other BRD types had no significant effect on risk of capture of either sharks and rays or teleosts. A forest plot of each study did not reveal any outliers (Figure S1).

Twelve studies reported a single species of shark or ray caught as by-catch (Table S1, Figure S2). Effect sizes were highly variable, and there was no clear trend in capture risk across IUCN threat status categories. However, one study found that electropositive gears reduced capture of endangered juvenile scalloped hammerhead (*Sphyrna lewini*) by 57%. Another study found that circle hooks reduced the catch of pelagic stingray (*Pteroplatytrygon violacea*), a least concern species, by almost 75%.

## Discussion

Two of the main benefits of meta-analyses are that they bear a greater external validity than the results of any individual experiment (Shadish *et al.* 2002) and they allow a quantitative assessment of the overall influence of a predictor on an outcome measure. Our meta-analysis of the effectiveness of longline BRDs suggests that, overall, these devices reduce the risk of shark and ray capture by only 12% compared with standard hooks, and that this difference is marginally non-significant. By comparison, turtle excluder devices, a common type of BRD designed to reduce sea turtle by-catch in trawl nets, produce 99% reductions in turtle catch relative to standard gear (Brewer *et al.* 2006) and are broadly effective enough to be mandatory for usage in US trawl fisheries (OECD 2005).

Our conclusion is likely to be conservative because publication bias – a common concern in meta-analysis – tends to favour significant studies, leading to a propensity for meta-analyses to report exaggerated overall effects (Rothstein *et al.* 2006). The great diversity of BRD types accounted for ~16% of overall variation in capture risk, with one device, raised lines, appearing to be effective at decreasing by-catch of sharks and rays. A great deal of variation in capture risk remains unexplained, which may be attributed to variation in ecosystems, fishing gears and/or species. We also note that our meta-analysis only incorporated mitigation technology reported in published literature, and the possibility remains that other, more effective gears exist but have not yet been experimentally tested. In addition, other approaches that we did not classify as a BRD, including night-setting, deep-setting and bait-swapping, could be effective but were beyond the scope of our analysis.

Circle hooks are the best-studied type of longline BRDs, both for their effect on shark and ray by-catch as well as their functionality for catching teleosts. Circle hooks slightly increased the risk of capturing sharks and rays caught on longlines relative to control gear (7.6% non-significant increase; see also Godin *et al.* 2012). However, the propensity of circle hooks to promote jaw-hooking rather than gut-hooking improves the prospects of post-release survival for sharks and rays and potentially other hooked species (Read 2007; Godin *et al.* 2012; but see Ward *et al.* 2009). Circle hooks also appeared to be effective at reducing the by-catch of one species, the pelagic stingray (Figure S2). For these reasons, and because they do not reduce target catches (Fig. 2) and they cost the same as traditional J-hooks (USD ~$0.40 per hook, Pacific Net and Twine Ltd. Richmond, British Columbia, Canada), they represent a potentially viable option for reducing harm caused by longline fishing.

Electropositive, magnetic and combined BRDs have received a disproportionate amount of coverage in popular media. Similar devices have been marketed as repellents to protect swimmers from shark attacks (Huveneers *et al.* 2012), and several patents have been granted or are currently pending for electropositive and magnetic-based shark repelling technology (e.g. Stowell 1980; Wynne 2006; Stroud 2007). The enthusiasm for these BRDs stems largely from the fact that these BRDs target a sensory system that is specific to cartilaginous fishes, and from the substantial behavioural effects observed on captive sharks in controlled laboratory conditions (e.g. Stoner and Kaimmer 2008; Rigg *et al.* 2009). However, the media-hyped suggestions that such BRDs could reduce shark by-catch by as much as 70% (e.g. Shapiro 2012) were not supported by our meta-analysis of rigorous field studies. Electropositive, magnetic and combined BRDs all failed overall to reduce shark and ray by-catch significantly (non-significant reductions of 18%, 32% and 29%, respectively, relative to control gear). One study found a reduction in catch of scalloped hammerhead, but that result was for juveniles and was inconsistent with the effects on adult sharks (Hutchinson *et al.* 2012). Furthermore, it seems unlikely that this technology would be adopted commercially even if effective, due to the high cost of electropositive and magnetic alloys, their hazardous manufacturing process (Stoner and Kaimmer 2008), their poor durability as they dissolve quickly in sea water (Kaimmer and Stoner 2008) and issues with large-scale deployment (e.g. if magnets stick together, Rigg *et al.* 2009). It is unlikely that these issues can be resolved with future improvements, as the problems are innate to the gear itself (i.e. electropositive alloys must dissolve to create the electric field). Electric fields in water can also be generated by a powered system that emits electrical pulses. However, the only experiment using such a device (which could not be included in our meta-analysis because the test did not employ fishing gear) demonstrated an effect on shark behaviour, but no effect on the propensity of sharks to take bait attached to a pulsating device (Huveneers *et al.* 2012).

Two types of BRDs may represent promising avenues for future research. Monofilament nylon leaders have been widely recommended as an effective tool to reduce by-catch and improve target catch rates, and they are attractive because of their low cost. A single study has so far directly tested the difference in catch between wire and nylon leaders in the field (Ward *et al.* 2008). Monofilament nylon leaders were 58% less likely to catch sharks and rays than wire leaders, but the reduction was not statistically significant owing to the large confidence interval predicted by our model. However, the effect size of the single study that tested monofilament nylon leaders is significant when calculated on its own (i.e. not as part of a meta-analysis, Figure S1). Additional research is needed to confirm whether this gear is effective across species. However, the potential population-level impacts of hooks attached to released sharks should also be evaluated, as ingested hooks can promote disease and cause delayed mortality in affected sharks (Bansemer and Bennett 2010). In addition, longline fisheries that target sharks have paradoxically reported increases in catch when using monofilament leaders (Berkeley and Campos 1988; Branstetter and Musick 1993). Tarred multifilament nylon leaders did not reduce the risk of shark and ray capture but instead, reduced the risk of teleost catch by 66%, suggesting that this would be an unsuitable modification for by-catch reduction.

The success observed when raising demersal longlines off the ocean bottom using floats is similarly promising. Elevating the gear in the water column places it in a position where it is less likely to be encountered by demersal sharks and rays (Afonso *et al.* 2011) and reduced the risk of capture by 66% relative to non-raised gear. This approach of physically separating gear from non-target species is analogous to the weighting of pelagic longlines to sink hooks quickly beyond the reach of diving seabirds, which has been shown to reduce seabird by-catch significantly (Dietrich *et al.* 2008). It also highlights the potential importance of gear deployment depth in affecting by-catch rates (Ward and Myers 2005). Further research into how to effectively place gear away from non-target species is therefore also warranted.

The incidental capture of sharks and rays in longline fisheries occurs around the world and affects a wide range of shark and ray species (Gilman *et al.* 2008). In terms of devising effective conservation strategies to tackle this source of shark and ray mortality, our results have three main implications. First, although a few individual studies have demonstrated that specific BRDs are effective, the weight of evidence across all studies suggests limited success so far. The effectiveness of a given BRD appears to be very context dependent. Thus, perhaps not surprisingly, a single technological solution that reduces shark and ray by-catch across fisheries has yet to be found. Second, very few of the wide range of BRDs tested appear to affect the catches of targeted teleosts. This is an important finding because maintaining valuable catches is essential for the acceptance of BRDs, and other conservation measures, by the fishing industry. However, we also note that many studies did not assess teleost catch, and none assessed BRD-induced shifts in body size and price differentials among species, oversights that must change in future work. Finally, there are understudied classes of BRDs that could represent promising avenues of future work. In particular, raised demersal longlines and monofilament nylon leaders could emerge as potentially cost-effective tools for mitigating shark and ray mortality on longline gear, but their impacts on by-catch, target catch and their practicality for use in fisheries need to be rigorously assessed.

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## References

Afonso, A., Hazin, F., Carvalho, F. *et al.* (2011) Fishing gear modifications to reduce elasmobranch mortality in pelagic and bottom longline fisheries off Northeast Brazil. *Fisheries Research* **108**, 336–343.

Bansemer, C.S. and Bennett, M.B. (2010) Retained fishing gear and associated injuries in the east Australian grey nurse sharks (*Carcharias taurus*): implications for population recovery. *Marine and Freshwater Research* **61**, 97–103.

Berkeley, S.A. and Campos, W.L. (1988) Relative abundance and fishery potential of pelagic sharks along Florida's east coast. *Marine Fisheries Review* **50**, 9–16.

Bolten, A.B. and Bjorndal, K.A. (2005) Experiment to evaluate gear modification on rates of sea turtle bycatch in the swordfish longline fishery in the Azores. *Final Project Report submitted to the U.S. National Marine Fisheries Service*. NOAA Award Number NA03NMF4540204.

Branstetter, S. and Musick, J.A. (1993) Comparisons of shark catch rates on longlines using rope/steel (Yankee) and monofilament gangions. *Marine Fisheries Review* **55**, 4–9.

Brewer, D., Heales, D., Milton, D. *et al.* (2006) The impact of turtle excluder devices and bycatch reduction devices on diverse tropical marine communities in Australia's northern prawn trawl fishery. *Fisheries Research* **81**, 176–188.

Brill, R., Bushnell, P., Smith, L. *et al.* (2009) The repulsive and feeding-deterrent effects of electropositive metals on juvenile sandbar sharks (*Carcharhinus plumbeus*). *Fishery Bulletin* **107**, 298–307.

Carruthers, E.H., Schneider, D.C. and Neilson, J.D. (2009) Estimating the odds of survival and identifying mitigation opportunities for common bycatch in pelagic longline fisheries. *Biological Conservation* **142**, 2620–2630.

Cox, T.A., Lewison, R.L., Zydelis, R., Crowder, L.B., Safina, C. and Read, A.J. (2007) Comparing effectiveness of experimental and implemented bycatch reduction measures: the ideal and the real. *Conservation Biology* **21**, 1155–1164.

Curran, D. and Bigelow, K. (2011) Effects of circle hooks on pelagic catches in the Hawaii-based tuna longline fishery. *Fisheries Research* **109**, 265–275.

Dietrich, K.S., Meluin, E.F. and Conquest, L. (2008) Integrated weight longlines with paired streamer lines – best practice to prevent seabird bycatch in demersal longline fisheries. *Biological Conservation* **141**, 1793–1805.

Domingo, A., Pons, M., Jiménez, S., Miller, P., Barceló, C. and Swimmer, Y. (2012) Circle hook performance in the Uruguayan pelagic longline fishery. *Bulletin of Marine Science* **88**, 499–511.

Dulvy, N.K., Baum, J.K., Clarke, S. *et al.* (2008) You can swim but you can't hide: the global status and conservation of oceanic pelagic sharks and rays. *Aquatic Conservation-Marine and Freshwater Ecosystems* **18**, 459–482.

FAO (2002) Fishing technology equipments. Bycatch Reduction Devices (BRDs). In: *Technology Fact Sheets* (eds V. Crespi and J. Prado). FAO Fisheries and Aquaculture Department, Rome, Available at: http://www.fao.org/fishery/equipment/brd/en (accessed 16 August 2013).

García, V.B., Lucifora, L.O. and Myers, R.A. (2008) The importance of habitat and life history to extinction risk in sharks, skates, rays and chimaeras. *Proceedings of the Royal Society B: Biological Sciences* **275**, 83–89.

Gilman, E., Clarke, S., Brothers, N. *et al.* (2007) Shark depredation and unwanted bycatch in pelagic longline fisheries: industry practices and attitudes, and shark avoidance strategies. In: *Western Pacific Regional Fishery Management Council, Honolulu, Hawaii. ISBN 1-934061-06-9*.

Gilman, E., Clarke, S., Brothers, N. *et al.* (2008) Shark interactions in pelagic longline fisheries. *Marine Policy* **32**, 1–18.

Godin, A.C., Carlson, J.K. and Burgener, V. (2012) The effect of circle hooks on shark catchability and at-vessel mortality rates in longlines fisheries. *Bulletin of Marine Science* **88**, 469–483.

Godin, A.C., Wimmer, T., Wang, J.H. and Worm, B. (2013) No effect from rare-earth metal deterrent on shark bycatch in a commercial pelagic longline trial. *Fisheries Research* **143**, 131–135.

Grantham, H.S., Petersen, S.L. and Possingham, H.P. (2008) Reducing bycatch in the South African pelagic longline fishery: the utility of different approaches to fisheries closures. *Endangered Species Research* **5**, 291–299.

Harrison, F. (2011) Getting started with meta-analysis. *Methods in Ecology and Evolution* **2**, 1–10.

Hedges, L.V. and Olkin, I. (1985) *Statistical Methods for Meta-Analysis*. Academic Press, San Diego, CA, p. 369.

Hedges, L.V. and Pigott, T.D. (2004) The power of statistical tests for moderators in meta-analysis. *Psychological Methods* **9**, 426–445.

Hutchings, J.A., Myers, R.A., García, V.B., Lucifora, L.O. and Kuparinen, A. (2012) Life-history correlates of extinction risk and recovery potential. *Ecological Applications* **22**, 1061–1067.

Hutchinson, M., Wang, J.H., Swimmer, Y. *et al.* (2012) The effects of a lanthanide metal alloy on shark catch rates. *Fisheries Research* **131–133**, 45–51.

Huveneers, C., Rogers, P.J., Semmens, J. *et al.* (2012) *Effects of the Shark Shield™ electric deterrent on the behaviour of white sharks (Carcharodon carcharias)*. South Australian Research and Development Institute: SARDI Publication No F2012/000123-1, Research Report Series No. 632.

Ingram, W., Henwood, T., Grace, M., Jones, L., Driggers, W. and Mitchell, K. (2005) *Catch Rates, Distribution and Size Composition of Large Coastal Sharks Collected during NOAA Fisheries Bottom Longline Surveys from the U.S. Gulf of Mexico and U.S.* Atlantic Ocean. National Marine Fisheries Service, Southeast Fisheries Science Center, Pasagoula, MS – SEDAR 11 LCS05/06-DW-27.

IUCN (2012) *IUCN Red List of Threatened Species*. Version 2012.2. Available at: www.iucnredlist.org (accessed 18 June 2013).

Kaimmer, S. and Stoner, A.W. (2008) Field investigation of rare-earth metal as a deterrent to spiny dogfish in the Pacific halibut fishery. *Fisheries Research* **94**, 43–47.

Kennelly, S.J. (2007) By-catch reduction in the world's fisheries. In: *Reviews: Methods and Technologies in Fish Biology and Fisheries*, Vol. 7 (ed. J.L. Nielsen). Springer, Dordrecht, The Netherlands, p. 289.

Kim, S.S., Moon, D.Y., An, D.H. and Koh, J.R. (2006) Comparison of circle hooks and J hooks in the catch rate of target and bycatch species taken in the Korean tuna longline fishery. *Western and Central Pacific Fisheries Commission, scientific committee second regular session. 7–18 August 2006, Manila, Philippines. WCPFC-SC2-2006/EB WP-12.*

Kim, S.S., An, D.H., Moon, D.Y. and Hwang, S.J. (2007) Comparison of circle hook and J hook catch rate for target and bycatch species taken in the Korean tuna longline fishery during 2005–2006. *Western and Central Pacific Fisheries Commission, scientific committee third regular session. 13-24 August 2007, Honolulu, United States of America. WCPFC-SC3-EB SWG/WP-11.*

Koricheva, J., Gurevitch, J. and Mengeresen, K. (2013) *Handbook of Meta-analysis in Ecology and Evolution*, Princeton University Press, Princeton, NJ, p. 520.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G. and The Prisma Group (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Medicine* **6**, e1000097.

Molina, J.M. and Cooke, S.J. (2012) Trends in shark bycatch research: current status and research needs. *Reviews in Fish Biology and Fisheries* **22**, 719–737.

Murray, R.W. (1960) Electrical sensitivity of the ampullae of Lorenzini. *Nature* **187**, 957.

O'Connell, C.P., Abel, D.C., Stroud, E.M. and Rice, P.H. (2011) Analysis of permanent magnets as elasmobranch bycatch reduction devices in hook-and-line and longline trials. *Fishery Bulletin* **109**, 394–401.

O'Connell, C.P., He, P., Joyce, J., Stroud, E.M. and Rice, P.H. (2014) Effects of the SMART™ (Selective Magnetic and Repellent-Treated) hook on spiny dogfish catch in a longline experiment in the Gulf of Maine. *Ocean & Coastal Management* **97** DOI: 10.1016/j.ocecoaman.2012.08.002.

OECD (2005) Adapting turtle-excluder devices to local conditions. In: *Environmental Requirements and Market Access*. OECD publishing, Paris, France, pp. 165–175, doi:10.1787/9789264013742-15-en.

Pacheco, J.C., Kerstetter, D.W., Hazin, F.H. *et al.* (2011) A comparison of circle hook and J hook performance in a western equatorial Atlantic Ocean pelagic longline fishery. *Fisheries Research* **107**, 39–45.

Petersen, S.L., Honig, M.B., Ryan, P.G., Underhill, L.G. and Compagno, L.J. (2009) Pelagic shark bycatch in the tuna- and swordfish-directed longline fishery off southern Africa. *African Journal of Marine Science* **31**, 215–225.

Piovano, S., Clò, S. and Giacoma, C. (2010) Reducing longline bycatch: the larger the hook, the fewer the stingrays. *Biological Conservation* **143**, 261–264.

Promjinda, S., Siriraksophon, S., Darumas, N. and Chaidee, P. (2008) Efficiency of the circle hook in comparison with J-hook in longline fishery. *Bangladesh, Indian, Myanmar, Sri Lanka, Thailand Economic Cooperation*, 167–181.

R Development Core Team (2011) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Read, A.J. (2007) Do circle hooks reduce the mortality of sea turtles in pelagic longlines? A review of recent experiments. *Biological Conservation* **135**, 155–169.

Rigg, D.P., Peverell, S.C., Hearndon, M. and Seymour, J.E. (2009) Do elasmobranch reactions to magnetic fields in water show promise for bycatch mitigation? *Marine & Freshwater Research* **60**, 942–948.

Robbins, W.D., Peddemors, V.M. and Kennelly, S.J. (2011) Assessment of permanent magnets and electropositive metals to reduce the line-based capture of Galapagos sharks, Carcharhinus galapagensis. *Fisheries Research* **109**, 100–106.

Rothstein, H.R., Sutton, A.J. and Borenstein, M. (2006) *Publication Bias in Meta-Analysis: Prevention, Assessment and Adjustments*. Wiley, NJ.

Rücker, G., Schwarzer, G., Carpenter, J.R. and Schumacher, M. (2008) Undue reliance on $I^2$ in assessing heterogeneity may mislead. *BMC Medical Research Methodology* **8**, 79.

Sales, G., Giffoni, B.B., Fiedler, F.N. *et al.* (2010) Circle hook effectiveness for the mitigation of sea turtle bycatch and capture of target species in a Brazilian pelagic longline fishery. *Aquatic Conservation: Marine and Freshwater Ecosystems* **20**, 428–436.

Shadish, W.R., Cook, T.D. and Campbell, D.T. (2002) *Experimental and Quasi-Experimental Designs for Generalized Causal Inference*, Vol. Houghton Mifflin, Boston, MA.

Shapiro, A.D. (2012) Shark attacks: a magnetic solution? In: *PRI's The World*. BBC News.

Stevens, J.D., Bonfil, R., Dulvy, N.K. and Walker, P.A. (2000) The effects of fishing on sharks, rays, and chimaeras (chondrichthyans), and the implications for marine ecosystems. *ICES Journal of Marine Science: Journal du Conseil* **57**, 476–494.

Stone, H.H. and Dixon, L.K. (2001) A comparison of catches of swordfish, *Xiphias gladius*, and other pelagic species from Canadian longline gear configured with alternating monofilament and multifilament nylon gangions. *Fisheries Bulletin* **99**, 210–216.

Stoner, A.W. and Kaimmer, S.M. (2008) Reducing elasmobranch bycatch: laboratory investigation of rare earth metal and magnetic deterrents with spiny dogfish and Pacific halibut. *Fisheries Research* **92**, 162–168.

Stowell, W.R. (1980) Method of creating an electric field for shark repellent. *US Patent 4 211 980*.

Stroud, E.M. (2007) Elasmobranch-repelling electropositive metals and methods of use. *US Patent Application US 2007/0256623 A1*.

Swimmer, Y., Wang, J.H. and McNaughton, L. (2008) *Shark deterrent and incidental capture workshop, April 10-11, 2008*, Vol., U.S. Dep. Commer., NOAA Tech. Memo., NOAA-TM-NMFS-PIFSC-16.

Swimmer, Y., Suter, J., Arauz, R. *et al.* (2011) Sustainable fishing gear: the case of modified circle hooks in a Costa Rican longline fishery. *Marine Biology* **158**, 757–767.

Tallack, S.M.L. and Mandelman, J.W. (2009) Do rare-earth metals deter spiny dogfish? A feasibility study on the use of electropositive "mischmetal" to reduce the bycatch of *Squalus acanthias* by hook gear in the Gulf of Maine. *Ices Journal of Marine Science* **66**, 315–322.

Viechtbauer, W. (2005) Bias and efficiency of meta-analytic variance estimators in the random-effects model. *Journal of Educational and Behavioral Statistics* **30**, 261–293.

Viechtbauer, W. (2010) Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software* **36**, 1–48.

Ward, P. and Hindmarsh, S. (2007) An overview of historical changes in the fishing gear and practices of pelagic longliners, with particular reference to Japan's Pacific fleet. *Reviews in Fish Biology and Fisheries* **17**, 501–516.

Ward, P. and Myers, R.A. (2005) Inferring the depth distribution of catchability for pelagic fishes and correcting for variations in the depth of longline fishing gear. *Canadian Journal of Fisheries and Aquatic Sciences* **62**, 1130–1142.

Ward, P., Lawrence, E., Darbyshire, R. and Hindmarsh, S. (2008) Large-scale experiment shows that nylon leaders reduce shark bycatch and benefit pelagic longline fishers. *Fisheries Research* **90**, 100–108.

Ward, P., Epe, S., Kreutz, D., Lawrence, E., Robins, C. and Sands, A. (2009) The effects of circle hooks on bycatch and target catches in Australia's pelagic longline fishery. *Fisheries Research* **97**, 253–262.

Watson, J. and Kerstetter, D. (2006) Pelagic longline fishing gear: a brief history and review of research efforts to improve selectivity. *Marine Technology Society Journal* **40**, 6–11.

Watson, J.W., Epperly, S.P., Shah, A.K. and Foster, D.G. (2005) Fishing methods to reduce sea turtle mortality associated with pelagic longlines. *Canadian Journal of Fisheries and Aquatic Sciences* **62**, 965–981.

World Wildlife Fund (2011) WWF's International smart gear competition. (ed. M. Osmond). Available at: http://www.smartgear.org (accessed 16 August 2013).

Worm, B. and Myers, R.A. (2003) Meta-analysis of cod-shrimp interactions reveals top-down control in oceanic food webs. *Ecology* **84**, 162–173.

Wynne, B.M. (2006) Surfboard shark repellent system. *US Patent 7 037 153*.

Yokota, K., Kiyota, M. and Minami, H. (2006) Shark catch in a pelagic longline fishery: comparison of circle and tuna hooks. *Fisheries Research* **81**, 337–341.

Yokota, K., Kiyota, M. and Okamura, H. (2009) Effect of bait species and color on sea turtle bycatch and fish catch in a pelagic longline fishery. *Fisheries Research* **97**, 53–58. [In English].

Zhang, J. and Yu, K.F. (1998) What's the relative risk? A method of correcting the odds ratio in cohort studies of common outcomes. *JAMA: The Journal of the American Medical Association* **280**, 1690–1691.

## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Forest plot of each study.

**Figure S2.** Effects sizes of studies reporting a single species of shark or ray caught as bycatch, presented by IUCN Red List status.

**Table S1.** Full list of all shark and ray species reported across BRD types.

**Appendix S1.** Excel spreadsheet listing all papers which appeared during our literature search, including detailed reasons for exclusion for each paper not included in the final analysis.