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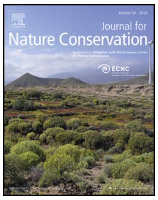

Review

Seabird longline bycatch reduction devices increase target catch while reducing bycatch: A meta-analysis

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ABSTRACT

Mortality during commercial fishing activities is a significant threat to many imperiled seabird species, and myriad technologies have been developed to reduce mortality during longline fishing operations. However, individual studies have never been combined in a quantitative manner to determine if seabird bycatch reduction devices (BRD) have a detrimental effect upon target species catch. We performed a meta-analysis of the longline fishery BRD literature to determine the general impact of BRD technology upon commercial fishing operations. There were relatively few papers with data suitable for a meta-analysis (15), therefore we pooled studies in the analysis with BRD and fishery related metrics included as covariates. Overall, we found no reduction in target fish catch. In fact, we found an increase in target catch of 9% (95% CI [1,17]) with BRD use. We show that this increase occurs while BRDs reduce seabird bycatch by 89% (95% CI [82,93]). These patterns do not change with respect to geographic location or BRD type, indicating that efforts to reduce seabird bycatch are generally effective under different conditions. Our review identifies research needed to ensure the generality of our findings and to better understand the impacts of BRD implementation upon seabird conservation and commercial fisheries.

Contents

1. Introduction

The capture of non-target species (bycatch) in commercial fisheries is a critical issue for fisheries management. Seabirds such as albatrosses and shearwaters are a significant component of global bycatch, and they can experience high levels of mortality when they become entangled in longline, gillnet, and trawl fisheries (Bull, 2007; Løkkeborg, 2011). The International Union for

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Conservation of Nature (IUCN) classifies half of all petrels and three quarters of all albatross species as threatened (Croxall et al., 2012; Stattersfield et al., 2000), due in part to the vast number of seabirds killed annually as bycatch (~160,000- 320,000; (Anderson et al., 2011). An increasing number of bycatch reduction devices (BRDs), mitigation strategies, avoidance methods, and policies have been implemented to reduce the capture of non-target species (Gilman, Brothers, & Kobayashi, 2005; Hall, Alverson, & Metuzals, 2000). Although the scientific community has given considerable attention to whether these attempts are successful in reducing seabird bycatch (ACAP, 2016a, 2016b; Croxall et al., 2012; Løkkeborg, 2011), very little attention has been directed towards the important question of how BRD implementation impacts the catch of target species. This is a critical question if we want to identify those management practices that bring the best financial and conservation outcomes (Wilcox & Donlan, 2007). It is also important to understand potential socioeconomic benefits if we are to encourage non-adopting fisheries to deploy BRDs that come with substantial economic and time costs.

A common expectation is that seabird bycatch mitigation measures will reduce target catch quantity by rendering gear less effective (Hall & Mainprize, 2005). From a fisheries perspective, reductions in bait lost to seabirds could lead to increases in target catch, which could help justify the additional financial and time costs required to deploy BRDs (Gandini & Frere, 2012). The goal for new and existing bycatch reducing technologies is to maintain target catch while reducing bycatch, and individual studies for some types of gear such as weighted long-lines do demonstrate this dynamic (ACAP, 2016a). However, there is evidence that some fisheries do better than others at maintaining target catch while preventing bycatch (Hall & Mainprize, 2005), and it is possible that some technologies might lead to increases in target catch (see discussion for rationale). Despite this important possibility, there have been no meta-analyses to determine the overall impact to commercial landings when BRDs are in use.

This study aims to bring together the relevant literature surrounding seabird bycatch reduction in longline fisheries, focusing specifically on the role that BRDs play in limiting or increasing target species catch and reducing fisheries-related seabird mortality. It is important to note that there are methods (non-technological solutions) of reducing bycatch, such as night setting and offal retention, which have been found to be effective (ACAP, 2016a). However, these methods do not typically produce data in the form of birds per hook, and we are unable to standardize them to units that allow inclusion in a meta-analysis. We evaluate the effect of seabird BRDs on the targeted catch of the longline fishery in each study to determine if BRD implementation impacts total catch. We then consider the effects of specific types of BRDs on seabird mortality and the location in which each study was conducted to determine if patterns in target catch follow commensurate decreases in seabird bycatch. We make recommendations for future research on topics or methods that we found lacking in our literature search, including socio-economic considerations (e.g., costs of BRD implementation).

2. Methods

2.1. Literature search

We searched four databases for papers to analyze: Bycatch.org, Web of Science, Google Scholar, and the Aquatic Sciences and Fisheries Abstract database. We used the search terms "bird", "marine", "bycatch reducti*", "deterr*", "discard", and "BRD", and collected pertinent papers from the first 200 results of each search. We also searched the references of candidate papers to identify studies that may not have been discovered in our initial search. We used broad search terms to capture as many papers as possible. We searched for bird papers to ensure that target catch data was paired with avian bycatch efforts, and to verify that avian bycatch was in fact being reduced during the studies that we included for study of target catch. We found many review papers, conference and working group proceedings, government publications, and primary research articles. The latter group of papers in particular produced the majority of the results we analyze here.

For inclusion in our meta-analysis, papers had to satisfy six general criteria (Fig. 1): (1) the paper had to contain data (i.e., no review or policy papers containing qualitative comparisons were retained); (2) birds had to be a taxa of interest (Procellariiformes, Charadriiformes, Suliformes); (3) the paper needed to focus on or contain data from longline fisheries; (4) BRDs had to be compared with non-BRD control treatments; (5) effort (in terms of deaths per hook) needed to be provided as well as the total number of hooks deployed per treatment; and (6) seabird mortality (rather than attack rate) needed to be documented. The use of a control (fishing gear without BRDs) contrasted against a BRD proved particularly limiting, accounting for nearly one third of our excluded papers (two papers made use of rigorous control treatments but provided summary data and we contacted the authors for the raw data). To avoid biasing our analysis with overly restrictive criteria (see Englund, Sarnelle, & Cooper, 1999), we adopted a general view of controls. Thus, we included studies in which the same fishing gear was deployed with and without BRDs, or two types of fishing gear were deployed as long as one was considered the industry standard and the other included bycatch reduction technology (e.g. circle hooks vs. standard j-hooks). We treated studies that alternated the BRD and control within the same set in the same fashion as those studies that alternated the treatment by set.

We encountered considerable variation across studies and we made the following three decisions when compiling data: (1) we aggregated all seabird bycatch numbers because some studies reported genus or species identifiers and other studies only reported number of total birds, (2) many studies employed multiple BRDs, but did not remove some in the control treatment (e.g., a regular line streamer was tested against a hybrid streamer); therefore, those technologies common to all sets are not mentioned because they were not tested against a non-BRD treatment, and (3) all variations of a BRD type were placed in a single category. For example, some studies use a single bird scaring line and others use double, or hybrid lines, and some studies differ in the style and brand of weighted long line.

Studies that compared the effects of BRDs upon targeted species catch had to meet all prior avian bycatch requirements for inclusion. It is also important to note that not all BRDs were initially developed for birds (i.e., circle hooks), but these data were included if the study design for avian effects contained a control. Each paper that was included in our analysis may have had a number of different comparisons. Every individual comparison of a BRD or combination of BRDs to a control was treated as a single study in the analysis.

2.2. Statistical analysis

We analyzed effects on target species catch first. Our measure of effect size was relative risk (RR), calculated as:

$$RR = \frac{a_i/n1_i}{b_i/n2_i}$$

for a study (i), a is the number of hooks that caught a targeted species while using BRD, b is the number of hooks that caught a targeted species without a BRD, $n1$ is the number of hooks in the

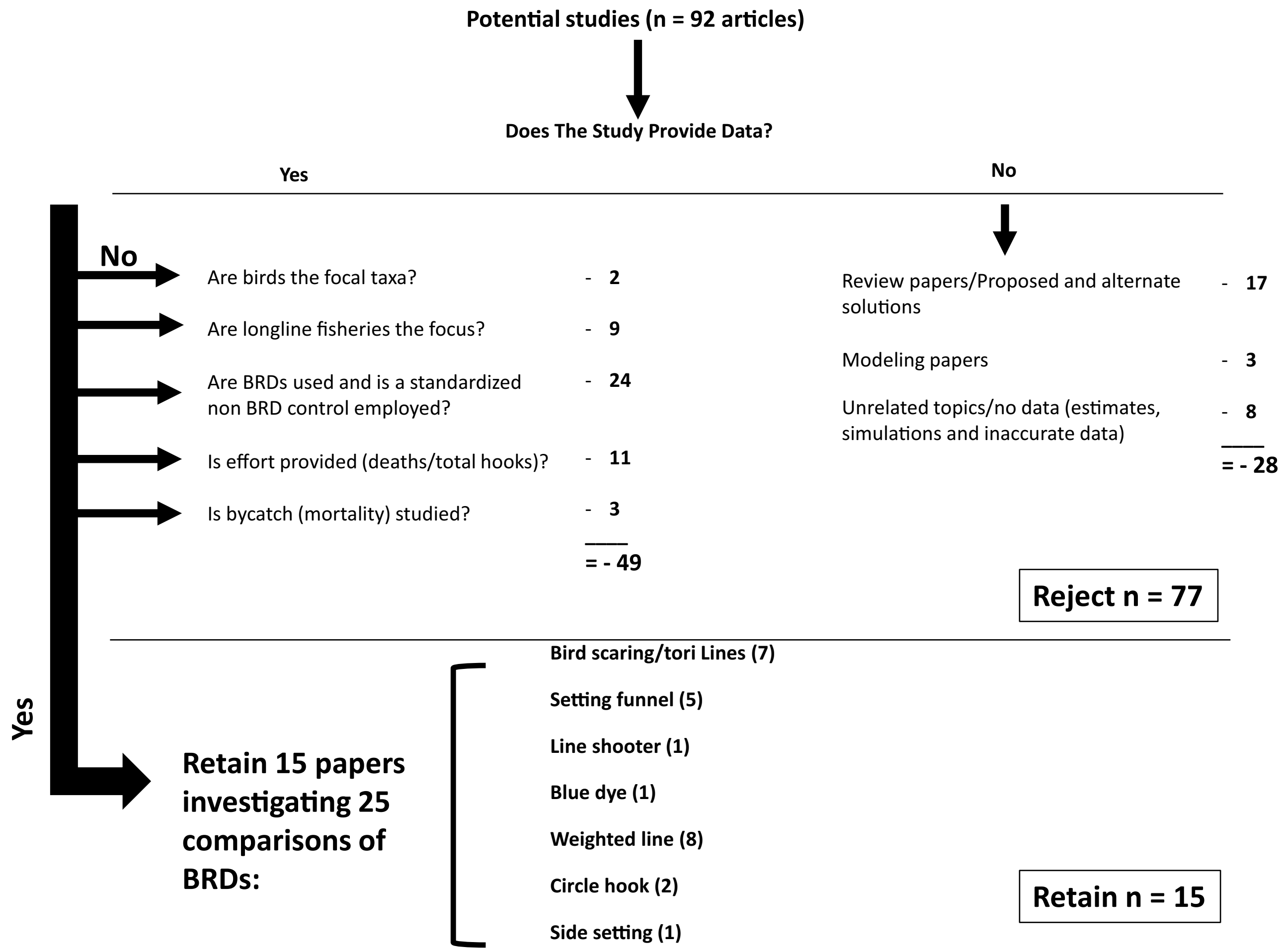


Fig. 1. Decision tree for inclusion of papers in the meta-analysis of bycatch reduction device effectiveness. Each paper had to satisfy five general requirements, otherwise it was removed from the pool of candidate papers. General categories of discarded papers are provided in the right-hand column.

study with a BRD, and $n2$ is the number of hooks in the study without a BRD (Borenstein, Hedges, Higgins, & Rothstein, 2009). We also used RR as the effect size for avian bycatch where a is the number of hooks in the study that caught a bird while using a BRD, b is the number of hooks that caught a bird without a BRD, and $n1$ and $n2$ are the same as above. We took the log of the RR to normalize the results and maintain symmetry in the analysis (Borenstein et al., 2009; Viechtbauer, 2010)

$$LogRR = ln(RR)$$

and approximate variance:

$$V_{LogRR} = \frac{1}{a_i} - \frac{1}{n1_i} + \frac{1}{b_i} - \frac{1}{n2_i}$$

where the approximated standard error is

$$SE_{LogRR} = \sqrt{V_{LogRR}}$$

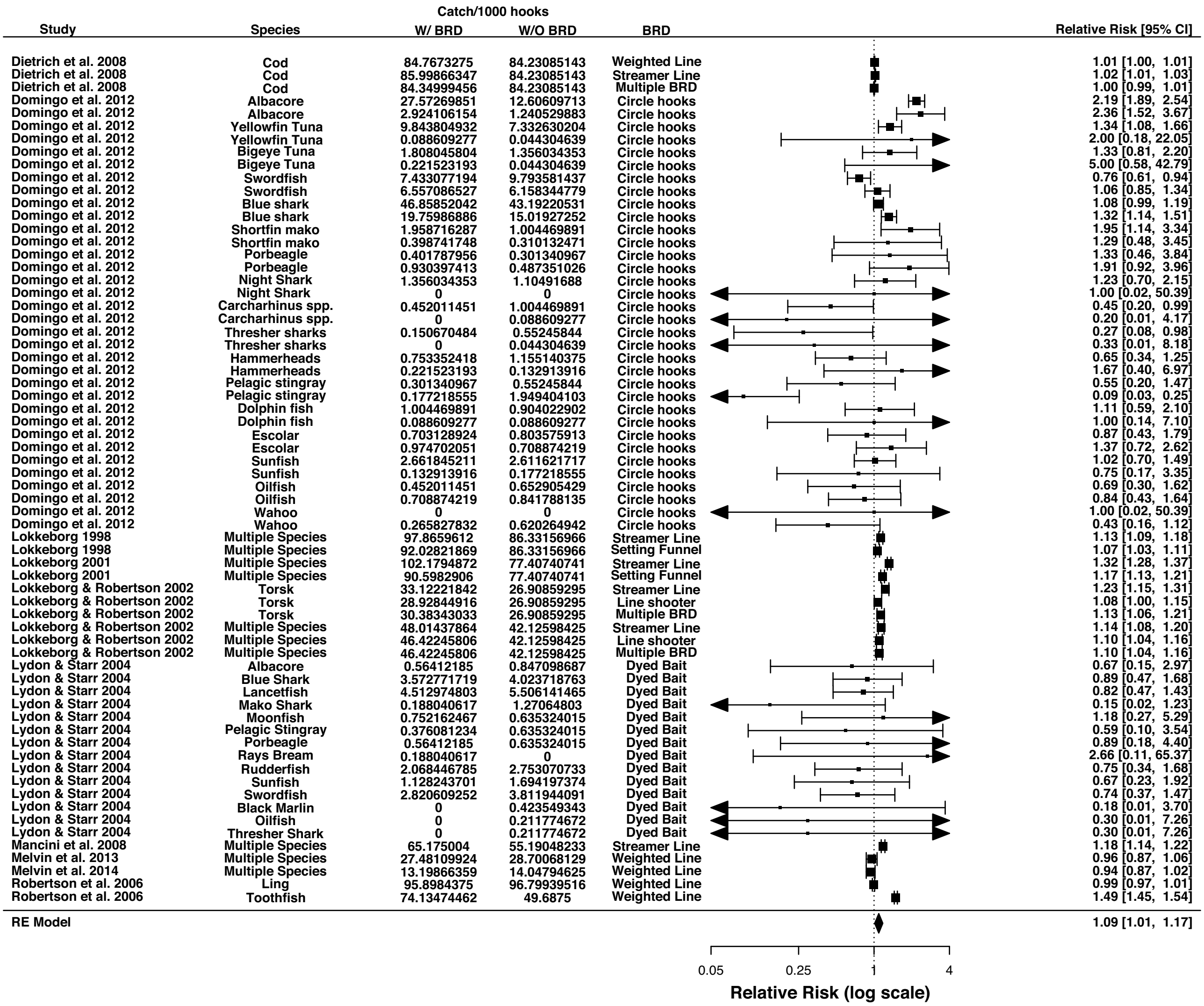
We considered the effect of BRDs in general (overall effect size) and the effect for each study to be significant if the 95% confidence interval (CI) did not include 1. If the CI is entirely less than 1, a reduction in target species caught or the number of bird deaths occurred. If the CI is entirely greater than 1, an increase in target species caught occurred or the number of seabird deaths increased.

2.3. *Random effects models and overall relative risk*

We used a random effects model to calculate an overall RR for target species catch via a random effects model across all BRD types and targeted species. We also calculated an overall RR for bird mortality across all BRD types and locations. A considerable amount of heterogeneity was expected in the data for each model, and the goal was to calculate a grand effect size. A random-effects model allowed us to do this while best accounting for the within-study error and variation in the true effect size (Borenstein et al., 2009). Heterogeneity (τ^2) was measured using a restricted maximum-likelihood estimator where τ^2 is the amount of heterogeneity in the true RR for a random-effects model. We also calculated Orwin's *Fail-safe N* for each model (Orwin, 1983) and performed Trim and Fill analysis (Duval & Tweedie, 2000) on the funnel plot if a model's fail-safe N was below the threshold 5K + 10, where K is the number of studies included in the model.

2.4. *Effects of covariates on relative risk*

We used a mixed-effects model that modified RR of target species catch by BRD type and type of fishery as different target species may require different methods of fishing (depth, hook size, bait, etc.). We also used a mixed-effects model that modified RR of bird mortality by BRD type, zone fished (pelagic or demersal) and location (ocean basin) of the study. This was to examine how the various methods of longline fishing may be differentially affected by the use of BRDs. Heterogeneity for the mixed effects models was measured in the same way as for the random-effects models, but here τ^2 is the amount of residual heterogeneity for a mixed-effects model (Viechtbauer, 2005, 2010). Significance of τ^2 was measured using Cochran's Q (Borenstein et al., 2009). These analyses were



Study	Species	Catch/1000 hooks W/ BRD	Catch/1000 hooks W/O BRD	BRD	Relative Risk [95% CI]
Dietrich et al. 2008	Cod	84.7673275	84.23085143	Weighted Line	1.01 [1.00, 1.01]
Dietrich et al. 2008	Cod	85.99866347	84.23085143	Streamer Line	1.02 [1.01, 1.03]
Dietrich et al. 2008	Cod	84.34999456	84.23085143	Multiple BRD	1.00 [0.99, 1.01]
Domingo et al. 2012	Albacore	27.57269851	12.60609713	Circle hooks	2.19 [1.89, 2.54]
Domingo et al. 2012	Albacore	2.924106154	1.240529883	Circle hooks	2.36 [1.52, 3.67]
Domingo et al. 2012	Yellowfin Tuna	9.843804932	7.332630204	Circle hooks	1.34 [1.08, 1.66]
Domingo et al. 2012	Yellowfin Tuna	0.088609277	0.044304639	Circle hooks	2.00 [0.18, 22.05]
Domingo et al. 2012	Bigeye Tuna	1.808045804	1.356034353	Circle hooks	1.33 [0.81, 2.20]
Domingo et al. 2012	Bigeye Tuna	0.221523193	0.044304639	Circle hooks	5.00 [0.58, 42.79]
Domingo et al. 2012	Swordfish	7.433077194	9.793581437	Circle hooks	0.76 [0.61, 0.94]
Domingo et al. 2012	Swordfish	6.557086527	6.158344779	Circle hooks	1.06 [0.85, 1.34]
Domingo et al. 2012	Blue shark	46.85852042	43.19220531	Circle hooks	1.08 [0.99, 1.19]
Domingo et al. 2012	Blue shark	19.75986886	15.01927252	Circle hooks	1.32 [1.14, 1.51]
Domingo et al. 2012	Shortfin mako	1.958716287	1.004469891	Circle hooks	1.95 [1.14, 3.34]
Domingo et al. 2012	Shortfin mako	0.398741748	0.310132471	Circle hooks	1.29 [0.48, 3.45]
Domingo et al. 2012	Porbeagle	0.401787956	0.301340967	Circle hooks	1.33 [0.46, 3.84]
Domingo et al. 2012	Porbeagle	0.930397413	0.487351026	Circle hooks	1.91 [0.92, 3.96]
Domingo et al. 2012	Night Shark	1.356034353	1.10491688	Circle hooks	1.23 [0.70, 2.15]
Domingo et al. 2012	Night Shark	0	0	Circle hooks	1.00 [0.02, 50.39]
Domingo et al. 2012	Carcharhinus spp.	0.452011451	1.004469891	Circle hooks	0.45 [0.20, 0.99]
Domingo et al. 2012	Carcharhinus spp.	0	0.088609277	Circle hooks	0.20 [0.01, 4.17]
Domingo et al. 2012	Thresher sharks	0.150670484	0.55245844	Circle hooks	0.27 [0.08, 0.98]
Domingo et al. 2012	Thresher sharks	0	0.044304639	Circle hooks	0.33 [0.01, 8.18]
Domingo et al. 2012	Hammerheads	0.753352418	1.155140375	Circle hooks	0.65 [0.34, 1.25]
Domingo et al. 2012	Hammerheads	0.221523193	0.132913916	Circle hooks	1.67 [0.40, 6.97]
Domingo et al. 2012	Pelagic stingray	0.301340967	0.55245844	Circle hooks	0.55 [0.20, 1.47]
Domingo et al. 2012	Pelagic stingray	0.177218555	1.949404103	Circle hooks	0.09 [0.03, 0.25]
Domingo et al. 2012	Dolphin fish	1.004469891	0.904022902	Circle hooks	1.11 [0.59, 2.10]
Domingo et al. 2012	Dolphin fish	0.088609277	0.088609277	Circle hooks	1.00 [0.14, 7.10]
Domingo et al. 2012	Escolar	0.703128924	0.803575913	Circle hooks	0.87 [0.43, 1.79]
Domingo et al. 2012	Escolar	0.974702051	0.708874219	Circle hooks	1.37 [0.72, 2.62]
Domingo et al. 2012	Sunfish	2.661845211	2.611621717	Circle hooks	1.02 [0.70, 1.49]
Domingo et al. 2012	Sunfish	0.132913916	0.177218555	Circle hooks	0.75 [0.17, 3.35]
Domingo et al. 2012	Oilfish	0.452011451	0.652905429	Circle hooks	0.69 [0.30, 1.62]
Domingo et al. 2012	Oilfish	0.708874219	0.841788135	Circle hooks	0.84 [0.43, 1.64]
Domingo et al. 2012	Wahoo	0	0	Circle hooks	1.00 [0.02, 50.39]
Domingo et al. 2012	Wahoo	0.265827832	0.620264942	Circle hooks	0.43 [0.16, 1.12]
Lokkeborg 1998	Multiple Species	97.8659612	86.33156966	Streamer Line	1.13 [1.09, 1.18]
Lokkeborg 1998	Multiple Species	92.02821869	86.33156966	Setting Funnel	1.07 [1.03, 1.11]
Lokkeborg 2001	Multiple Species	102.1794872	77.40740741	Streamer Line	1.32 [1.28, 1.37]
Lokkeborg 2001	Multiple Species	90.5982906	77.40740741	Setting Funnel	1.17 [1.13, 1.21]
Lokkeborg & Robertson 2002	Torsk	33.12221842	26.90859295	Streamer Line	1.23 [1.15, 1.31]
Lokkeborg & Robertson 2002	Torsk	28.92844916	26.90859295	Line shooter	1.08 [1.00, 1.15]
Lokkeborg & Robertson 2002	Torsk	30.38343033	26.90859295	Multiple BRD	1.13 [1.06, 1.21]
Lokkeborg & Robertson 2002	Multiple Species	48.01437864	42.12598425	Streamer Line	1.14 [1.08, 1.20]
Lokkeborg & Robertson 2002	Multiple Species	46.42245806	42.12598425	Line shooter	1.10 [1.04, 1.16]
Lokkeborg & Robertson 2002	Multiple Species	46.42245806	42.12598425	Multiple BRD	1.10 [1.04, 1.16]
Lydon & Starr 2004	Albacore	0.56412185	0.847098687	Dyed Bait	0.67 [0.15, 2.97]
Lydon & Starr 2004	Blue Shark	3.572771719	4.023718763	Dyed Bait	0.89 [0.47, 1.68]
Lydon & Starr 2004	Lancetfish	4.512974803	5.506141465	Dyed Bait	0.82 [0.47, 1.43]
Lydon & Starr 2004	Mako Shark	0.188040617	1.27064803	Dyed Bait	0.15 [0.02, 1.23]
Lydon & Starr 2004	Moonfish	0.752162467	0.635324015	Dyed Bait	1.18 [0.27, 5.29]
Lydon & Starr 2004	Pelagic Stingray	0.376081234	0.635324015	Dyed Bait	0.59 [0.10, 3.54]
Lydon & Starr 2004	Porbeagle	0.56412185	0.635324015	Dyed Bait	0.89 [0.18, 4.40]
Lydon & Starr 2004	Rays Bream	0.188040617	0	Dyed Bait	2.66 [0.11, 65.37]
Lydon & Starr 2004	Rudderfish	2.068446785	2.753070733	Dyed Bait	0.75 [0.34, 1.68]
Lydon & Starr 2004	Sunfish	1.128243701	1.694197374	Dyed Bait	0.67 [0.23, 1.92]
Lydon & Starr 2004	Swordfish	2.820609252	3.811944091	Dyed Bait	0.74 [0.37, 1.47]
Lydon & Starr 2004	Black Marlin	0	0.423549343	Dyed Bait	0.18 [0.01, 3.70]
Lydon & Starr 2004	Oilfish	0	0.211774672	Dyed Bait	0.30 [0.01, 7.26]
Lydon & Starr 2004	Thresher Shark	0	0.211774672	Dyed Bait	0.30 [0.01, 7.26]
Mancini et al. 2008	Multiple Species	65.175004	55.19048233	Streamer Line	1.18 [1.14, 1.22]
Melvin et al. 2013	Multiple Species	27.48109924	28.70068129	Weighted Line	0.96 [0.87, 1.06]
Melvin et al. 2014	Multiple Species	13.19866359	14.04794625	Weighted Line	0.94 [0.87, 1.02]
Robertson et al. 2006	Ling	95.8984375	96.79939516	Weighted Line	0.99 [0.97, 1.01]
Robertson et al. 2006	Toothfish	74.13474462	49.6875	Weighted Line	1.49 [1.45, 1.54]
RE Model					1.09 [1.01, 1.17]

Fig. 2. Forest plot of the individual effect size estimates (relative risk of target species catch) for each study included in the meta-analysis with 95% confidence intervals (CI), the target species, the number of the target species per hook for each study with and without bycatch reduction devices, and the overall effect size from the random-effects (RE) model. Squares are centered on the mean estimated effect size for each study, and the size of a square indicates the weight its corresponding study received in the calculation of the overall effect size. Therefore, a square may be large enough to engulf the graphical representation of the 95% CI, making it appear that there is no interval or that the interval is within the bounds of the square. Neither of these is true for any study, and this is an artifact of using the size of the squares to represent the weight of each study. The arrow indicates that the 95% CI extended beyond the bounds of the scale in the figure. The actual numbers for the mean and 95% CI are given at the right hand side of the figure. The diamond indicates the overall effect size.

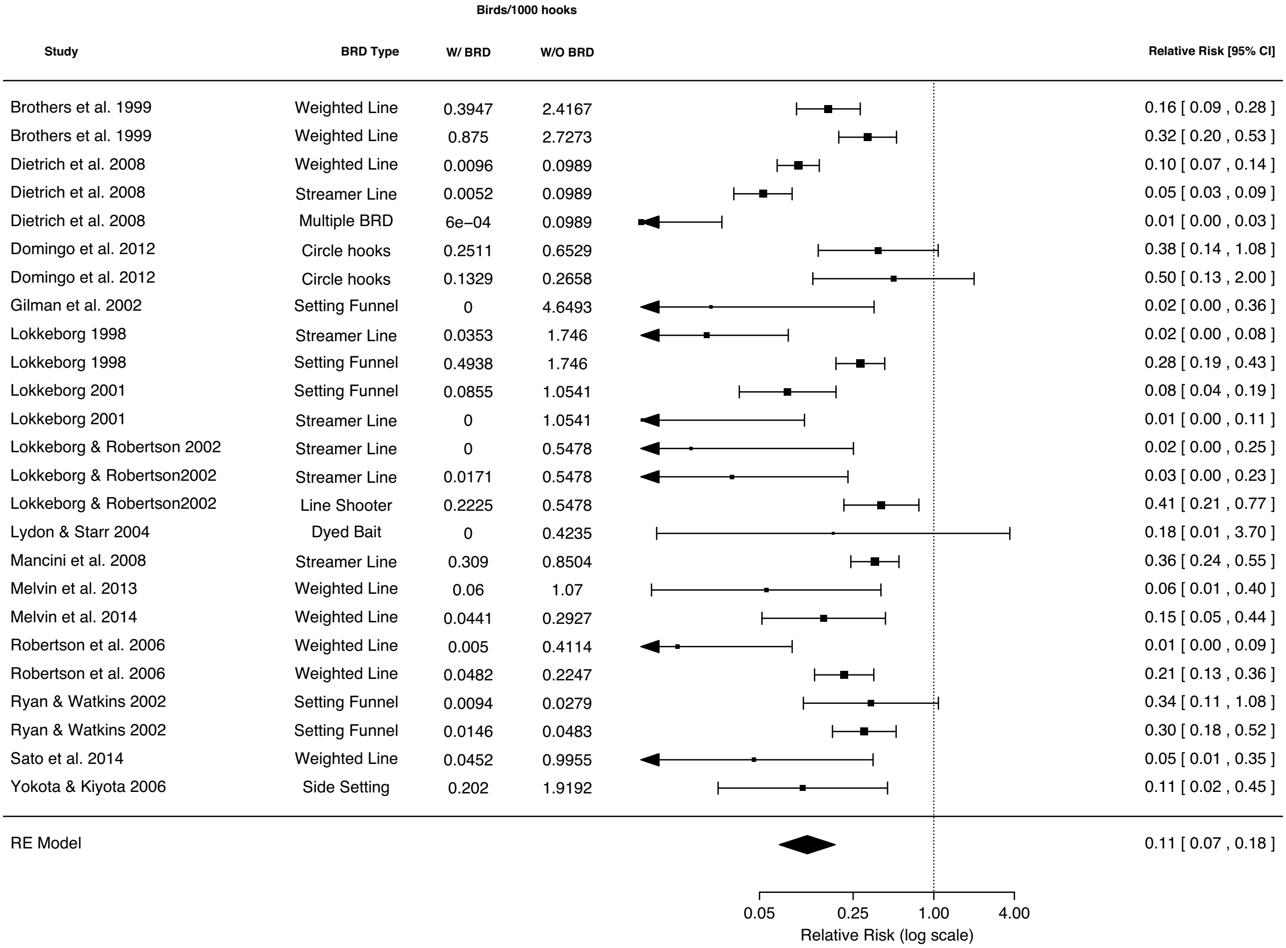
conducted using the 'metafor' package in R (R Development Core Team, 2011; Viechtbauer, 2010).

3. Results

3.1. Literature search

We identified 92 candidate manuscripts through our search process. Of these, 77 did not meet our search criteria, leaving us with 15 papers from which to extract data (Fig. 1) (Brothers, Gales, & Reid, 1999; Dietrich, Melvin, & Conquest, 2008; Domingo et al., 2012; Gilman et al., 2002; Løkkeborg, 1998, 2001; Løkkeborg & Robertson, 2002; Lydon & Starr, 2005; Mancini et al., 2009; Melvin, Guy, & Read, 2013, 2014; Robertson et al., 2006; Ryan & Watkins, 2002; Sato et al., 2014; Yokota & Kiyota, 2006). This number of papers in the analysis was similar to another recent bycatch meta-analysis for sharks and rays (Favaro & Cote, 2015). Failure to include a standardized control or employ a BRD (n = 24) was the primary reason for a study's exclusion. In general, our search terms were successful at finding papers focused on seabirds (two papers studied other orders). We did find papers that investigated fishing gear other than long lines (e.g., trawlers, gill nets), but there is no standard way to compare these disparate gear types and we omitted them from our analysis (n = 9). Finally, our search uncovered a number of informative but unusable review papers that summarized BRD type and alternate means of reducing bycatch (fleet communication, temporal management), simulation and modeling studies of bycatch effects upon populations, studies using attack rates as a proxy for bycatch (which provided insufficient detail for standardization), and papers that used either gross averages or hypothetical numbers (without providing birds/hook) to model the impacts of fishery bycatch on target fish catch (n = 28).

Out of the 15 papers suitable for inclusion, we found data for 25 combinations of BRD effects on seabird mortality. Ten of the 15 papers had data suitable for the analysis of target catch patterns, and we found 66 unique BRD and target fish combinations. As an example, one study had weighted lines and bird-scaring lines in one treatment, contrasted against unweighted gear without bird scaring lines as a control. Another treatment in the same study was weighted versus unweighted gear as a control, and



		Birds/1000 hooks		
Study	BRD Type	W/ BRD	W/O BRD	Relative Risk [95% CI]
Brothers et al. 1999	Weighted Line	0.3947	2.4167	0.16 [0.09 , 0.28]
Brothers et al. 1999	Weighted Line	0.875	2.7273	0.32 [0.20 , 0.53]
Dietrich et al. 2008	Weighted Line	0.0096	0.0989	0.10 [0.07 , 0.14]
Dietrich et al. 2008	Streamer Line	0.0052	0.0989	0.05 [0.03 , 0.09]
Dietrich et al. 2008	Multiple BRD	6e−04	0.0989	0.01 [0.00 , 0.03]
Domingo et al. 2012	Circle hooks	0.2511	0.6529	0.38 [0.14 , 1.08]
Domingo et al. 2012	Circle hooks	0.1329	0.2658	0.50 [0.13 , 2.00]
Gilman et al. 2002	Setting Funnel	0	4.6493	0.02 [0.00 , 0.36]
Lokkeborg 1998	Streamer Line	0.0353	1.746	0.02 [0.00 , 0.08]
Lokkeborg 1998	Setting Funnel	0.4938	1.746	0.28 [0.19 , 0.43]
Lokkeborg 2001	Setting Funnel	0.0855	1.0541	0.08 [0.04 , 0.19]
Lokkeborg 2001	Streamer Line	0	1.0541	0.01 [0.00 , 0.11]
Lokkeborg & Robertson 2002	Streamer Line	0	0.5478	0.02 [0.00 , 0.25]
Lokkeborg & Robertson2002	Streamer Line	0.0171	0.5478	0.03 [0.00 , 0.23]
Lokkeborg & Robertson2002	Line Shooter	0.2225	0.5478	0.41 [0.21 , 0.77]
Lydon & Starr 2004	Dyed Bait	0	0.4235	0.18 [0.01 , 3.70]
Mancini et al. 2008	Streamer Line	0.309	0.8504	0.36 [0.24 , 0.55]
Melvin et al. 2013	Weighted Line	0.06	1.07	0.06 [0.01 , 0.40]
Melvin et al. 2014	Weighted Line	0.0441	0.2927	0.15 [0.05 , 0.44]
Robertson et al. 2006	Weighted Line	0.005	0.4114	0.01 [0.00 , 0.09]
Robertson et al. 2006	Weighted Line	0.0482	0.2247	0.21 [0.13 , 0.36]
Ryan & Watkins 2002	Setting Funnel	0.0094	0.0279	0.34 [0.11 , 1.08]
Ryan & Watkins 2002	Setting Funnel	0.0146	0.0483	0.30 [0.18 , 0.52]
Sato et al. 2014	Weighted Line	0.0452	0.9955	0.05 [0.01 , 0.35]
Yokota & Kiyota 2006	Side Setting	0.202	1.9192	0.11 [0.02 , 0.45]
RE Model				0.11 [0.07 , 0.18]

Fig. 3. Forest plot of the individual effect size estimates (relative risk of bird mortality) for each study included in the meta-analysis with 95% confidence intervals (CI), the number of bird deaths per hook for each study with and without bycatch reduction devices, and the overall effect size from the random-effects (RE) model. Squares are centered on the mean estimated effect size for each study, and the size of a square indicates the weight its corresponding study received in the calculation of the overall effect size. Arrows indicate that a 95% CI extended beyond the bounds of the scale in the figure. The actual numbers for the mean and 95% CI are given at the right hand side of the figure. The diamond indicates the overall effect size. Multiple BRD in Dietrich et al. comprises weighted lines and streamer lines.

no other technologies were included. Therefore, this paper provided two separate studies of BRD effects (i.e., weighted gear and bird scaring lines vs. unweighted lines and no bird scaring lines and simply weighted vs. unweighted lines). Finally, we found that most papers did not differentiate among bird species caught as bycatch whereas target catch was often identified to species. When reported, the majority of birds studied were in the family Procellariidae where they were typically lumped into one category. The other major groups, Laridae, Sulidae, and Diomedeidae were reported as bycatch in a few studies but were only differentiated by family.

3.2. Statistical analysis

BRD implementation increased the overall number of targeted fish caught (RR = 1.09, 95% CI = 1.01–1.17; Fig. 2). The percent relative effect when RR is greater than one is: % increase = (RR-1) * 100%, which yields a 9% increase in target catch (95% CI [1,17]). There was substantial heterogeneity in this model ($\tau^2 = 0.042$, SE = 0.013, Q (df = 65) = 1390.37, $p < 0.0001$). The fail-safe N for this model was 13, suggesting further analysis of the effects of publication bias. A Trim and Fill analysis (Fig. 4) suggests that 0 studies need to fall to the left and 13 studies need to fall to the right of the mean effect size in order to make the plot symmetrical. This suggests that our effect size is a conservative estimate because if we had missed studies, we likely missed those that would have increased support for our finding. Finally, there was no significant effect of BRD type ($\beta = -0.027$–0.039, p = 0.17) or fishery ($\beta = -0.014$–0.004, p = 0.27) on the quantity caught of each targeted species. Almost none of the heterogeneity was explained by these factors ($R^2 < 0.001$, p = 0.51), suggesting that the result of catching slightly more targeted species using BRDs did not change by BRD type or the species being targeted. The use of circle hooks showed a negative effect for some species, however the small sample size of studies using circle hooks in our analysis may have led to this effect being overshadowed by larger studies with more data.

In the same group of studies where overall target species catch increased, the use of BRDs lowered overall bird mortality (RR = 0.11, 95% CI = 0.07–0.18; Fig. 3). The percent relative effect when RR is less than one is: % decrease = (1-RR) * 100%, which yields an 89% decrease in bycatch mortality (95% CI [82,93]). Again, there was considerable heterogeneity among studies ($\tau^2 = 1.05$, SE = 0.41, Q (df = 24) = 129.03, $p < 0.001$). The fail-safe N for this model was 586, suggesting that this effect size is statistically robust. There was no significant effect of BRD type ($\beta = -0.399$–0.031, p = 0.09), zone fished ($\beta = -0.136$–1.762, p = 0.9) or location ($\beta = -0.231$–0.113, p=0.5) on RR of bird mortality. These factors explained very little of the heterogeneity in the data ($R^2 < 0.09$, p = 0.137). This suggests that, while substantial heterogeneity remains unexplained, it is not affected by the type of BRD in use, the zone that was fished or the location of the study. While it may be tempting to interpret this

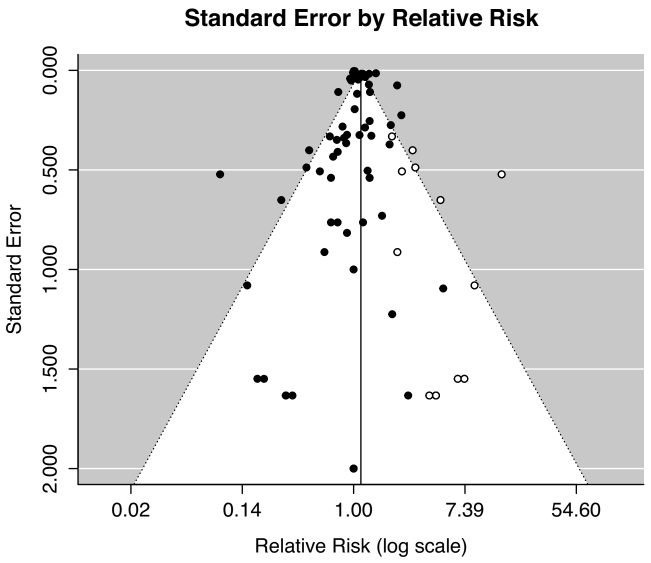


Fig. 4. Funnel plot including imputed studies from Trim and Fill analysis. Closed circles represent observed studies and open circles represent those studies imputed by the Trim and Fill analysis. The solid vertical at $x = 1.14$ represents the mean relative risk calculated by the Trim and Fill procedure after extreme studies were removed.

result as "all BRDs reduce bird mortality", we would hesitate to suggest the use of dyed bait or circle hooks for seabird BRDs as neither showed a reduction in bird deaths when analyzed alone. The small sample size of the studies using these BRDs allowed their individual results of "no effect" to be overshadowed by those BRDs for which much more data exists.

4. Discussion

We performed a meta-analysis to study how technologies designed to prevent the capture of seabirds during commercial fishing operations have impacted the capture of fish species targeted by fishing fleets. Overall we found that BRDs successfully reduce seabird bycatch with no reductions in target species catch. In fact, we found a small increase in target species catch; an important result with ramifications for policy and conservation efforts. This pattern did not change with respect to geographic location or BRD type in any of our analyses.

We propose three mechanisms by which seabird BRD deployment could be directly responsible for increases in target catch. First, an entangled or hook-caught bird will affect the movement of the line and its location in the water column, adversely affecting the catchability of the line (Bull 2007). Fewer birds becoming entangled on hooks allows more fish to become caught as the lines and hooks remain in proper position. Second, it is possible that a hook-caught bird may elicit an evasive response in the target species, acting as a deterrent (Litvak, 1993). Finally, in the event that a bird successfully removes the bait without getting caught, the missing bait will reduce the likelihood of landing a fish on that hook (Bull 2007). In all instances, fewer seabirds interacting with fishing gear could result in more opportunities for fish to become hooked. Therefore, the benefits of employing BRD technology may be directly responsible for increasing target catch, ultimately providing economic benefits as well as helping to conserve seabird populations.

There is the possibility that an increase in non-avian bycatch may occur when BRDs are deployed on fishing gear. For example, more baited hooks available to the target species also presents more baited hooks to non-target species such as sharks, sea turtles, and other fish and invertebrates (Clausen & Rodgveller, 2013; Gasco et al., 2015). Solutions that reduce entanglement of seabirds may increase risk for other non-targeted species. Further research is needed to fully understand the breadth of impacts associated with BRD deployment (ACAP, 2016a; Wilcox & Donlan, 2007) to ensure that a solution for one group of taxa does not create problems for others.

Our finding that BRD type does not explain any additional variation in either our target catch or seabird model suggests that, in general, many BRD technologies are effective on multiple fronts (as reported in many descriptive reviews: e.g., (ACAP, 2016a; Løkkeborg, 2011)). However, we urge caution in the interpretation of this finding because some technologies were represented by as little as one study. Furthermore, some technologies clearly demonstrate no-effect or a negative effect in our analysis (e.g. see blue-dyed bait and circle hooks, Figs. 2 and 3) (but see ACAP, 2016a). With ten papers for target catch data and five additional for seabird bycatch, seven different BRDs, seven different oceanic regions, and an unknown number of unique species comparisons against each BRD, we are probably far from fully understanding the manner in which specific species interact with BRD technologies. While our results offer strong support that BRDs are achieving their intended goals for fisheries and seabird conservation, we have highlighted the limited number of studies of BRD effectiveness that provide comparable measures of effect size (i.e., those that provide birds caught per hook and that employ a standardized control), and that would allow direct comparison of BRD efficacy. It should also be noted that the study with the largest estimated effect size for seabird bycatch reduction employed multiple BRDs (weighted line and streamer line) simultaneously (Fig. 3) (Dietrich et al., 2008). This implies that the benefits of using multiple BRDs may be additive (ACAP, 2016a), though a larger sample size is necessary to confirm this hypothesis. We also caution that comparison should be made only between similar gears and within the appropriate fisheries. For example, the category 'weighted line' comprises different styles of weight integration (e.g. weighted branch lines and integrated-weight longline) and both pelagic and demersal fisheries, although there was no significant effect of 'zone fished' in our analysis.

This review describes technologies that have been used extensively for many years and are still relied upon heavily. Newer technologies are currently in use or are in development, but their performance in controlled studies has not been evaluated in published studies (but see underwater bait setting system: Robertson, Ashworth, Ashworth, Carlyle, & Candy, 2015). However, some (e.g., 'hook pods' and 'smart tuna hooks') have been deemed extremely effective by ACAP and are recommended as single use technologies in areas where highly threatened species are present (ACAP, 2016a). It remains to be seen how the newer generation of technologies will impact target catch.

5. Conclusions

To more fully understand which BRDs are successful at eliminating bycatch without impacting target fisheries, we suggest three lines of research. First, determine the economic impact of BRD deployment to fishers and fisheries in general (Campbell & Cornwell, 2008; Wilcox & Donlan, 2007). For instance, it is not clear if the upfront costs of BRD technology are recovered during the lifetime of the gear, the extent to which particular gear types require additional crew members to deploy, and if additional safety risks are cause for concern (see Melvin et al. (2001) for a discussion of safety risk tradeoffs when adding weight to longlines). Some technologies such as integrated weight longlines do not require additional crew members and are safer, but are more costly to manufacture. Do the benefits outweigh the increased financial costs? Bull (2007) states that the additional cost of integrated weight longlines will likely be compensated by increased bait retention and target catch as seabird interactions with fishing gear decreases. Do other options such as predator control on seabird breeding grounds provide greater return-on-investment, providing pathways for fishermen through compensatory mitigation to help finance seabird conservation (Wilcox & Donlan, 2007)? Combined with bycatch mitigation at sea, this may prove to be an effective approach in certain circumstances. The second line of research is to determine the underlying causes of increased target catch. Many of the assumptions about reduced bait loss and more hooks available may in fact be true. However, additional research is required to ascertain the validity of these assumptions, and to determine if particular gear is more efficient than others. This research would inform our points above about the socio-economic considerations of bycatch reduction, and can be used to determine if increased catch generates enough profit to pay for mitigation measures. Finally, we propose that studies are needed in areas where seabirds are not present to understand if BRDs increase bycatch risk for other taxa. By testing BRDs against control treatments without the influence of seabird activity, researchers would be able to compare directly target and non-target bycatch to determine the effects upon commercial catch.

From a policy perspective, it seems likely that many approaches will result in a net benefit for seabird conservation and fisheries simultaneously. Therefore, non-adopting countries or developing countries with more severe economic limitations have a range of potential tools to select from based on affordability. Each method has recommendations in the literature appropriate for different conditions (Løkkeborg, 2011), and conservation groups like the Albatross Task Force (ATF) are working with countries hosting critical fisheries to employ or design BRDs commensurate with the skill level of local fisheries. While the number of studies that simultaneously employed multiple BRDs were limited (Fig. 3), our results show that fishing fleets can achieve comparable bycatch reductions with individual technologies, although we should point out that ACAP recommends employing multiple BRDs simultaneously to maximize bycatch reduction unless individual technologies can be shown to be as effective as multiple measures (ACAP, 2016a). This provides further support to the notion that the level of adoption can operate along a sliding scale of investment. The expected increase in target catch as BRD technology is employed should be used as a major incentive when encouraging adoption of BRDs. There is also a rich literature on other techniques such as night-setting, area-closures, and offal retention. These options may prove to be more efficient or cost effective for fisheries, including artisanal fisheries that do not have resources for more costly gear. Finally, researchers should be encouraged to report data for inclusion in meta-analyses. We recommend the development of a database for bycatch and target catch data, paired with effort data that will facilitate detailed analysis of new and existing technological impacts to fisheries and marine conservation.

Our meta-analysis of BRDs in longline fisheries has identified several important areas that we feel will improve the general understanding of bycatch mitigation and our ability to conserve at-risk seabird populations while preserving target catch. Several items, including the use of experimental controls and socio-economic costs of BRD adoption and deployment are also discussed in the voluntary International Guidelines on Bycatch Management and Reduction of Discards document (FAO, 2011). We strongly encourage international and regional fisheries management organizations to incorporate these practices in future policy to increase the amount of data available for analysis, and to bring important insights to seabird conservation

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Appendix A.

See Tables A1 and A2.

Table A1
Raw numbers from each study analyzed for avian bycatch in total number of birds killed with and without use of bycatch reduction devices (BRD), and number of hooks set with and without BRDs. Type of BRD used in each study can be found in Fig. 3.

Study	Birds W/BRD	Hooks W/BRD	Birds W/O BRD	Hooks W/O BRD
Brothers et al. (1999)	15	38000	87	36000
Brothers et al. (1999)	21	24000	60	22000
Dietrich et al. (2008)	32	3327172	344	3477423
Dietrich et al. (2008)	16	3049339	344	3477423
Dietrich et al. (2008)	2	3101747	344	3477423
Domingo et al. (2012)	5	19911	13	19911
Domingo et al. (2012)	3	22571	6	22571
Gilman et al. (2002)	0	4836	23	4947
Løkkeborg (1998)	2	56700	99	56700
Løkkeborg (1998)	28	56700	99	56700
Løkkeborg (2001)	6	70200	74	70200
Løkkeborg (2001)	0	70200	74	70200
Løkkeborg and Robertson (2002)	0	58420	32	58420
Løkkeborg and Robertson (2002)	1	58420	32	58420
Løkkeborg and Robertson (2002)	13	58420	32	58420
Lydon and Starr (2005)	0	5318	2	47722
Mancini et al. (2008)	29	93855	99	116415
Melvin et al. (2013)	1	16666	79	73831
Melvin et al. (2014)	4	90691	23	78588
Robertson et al. (2006)	1	199300	82	199300
Robertson et al. (2006)	18	373750	84	373750
Ryan and Watkins (2002)	3	317503	57	2045912
Ryan and Watkins (2002)	33	2255150	21	434598
Sato et al. (2014)	1	22100	11	11050
Yokota and Kiyota (2006)	2	9900	19	9000

Table A2
Raw numbers from each study analyzed for target species catch in total number of fish, and total number of hooks set with and without bycatch reduction devices (BRD). Type of BRD used in each study can be found in Fig. 2. Target species for each study can be found in Fig. 2.

Study	Catch W/BRD	Hooks W/BRD	Catch W/O BRD	Hooks W/O BRD
Dietrich et al. (2008)	128851	1520055	137543	1632929
Dietrich et al. (2008)	132421	1539803	137543	1632929
Dietrich et al. (2008)	128669	1525418	137543	1632929
Domingo et al. (2012)	549	19911	251	19911
Domingo et al. (2012)	66	22571	28	22571
Domingo et al. (2012)	196	19911	146	19911
Domingo et al. (2012)	2	22571	1	22571
Domingo et al. (2012)	36	19911	27	19911
Domingo et al. (2012)	5	22571	1	22571
Domingo et al. (2012)	148	19911	195	19911
Domingo et al. (2012)	148	22571	139	22571
Domingo et al. (2012)	933	19911	860	19911
Domingo et al. (2012)	446	22571	339	22571
Domingo et al. (2012)	39	19911	20	19911
Domingo et al. (2012)	9	22571	7	22571
Domingo et al. (2012)	8	19911	6	19911
Domingo et al. (2012)	21	22571	11	22571
Domingo et al. (2012)	27	19911	22	19911
Domingo et al. (2012)	0	22571	0	22571
Domingo et al. (2012)	9	19911	20	19911
Domingo et al. (2012)	0	22571	2	22571
Domingo et al. (2012)	3	19911	11	19911
Domingo et al. (2012)	0	22571	1	22571
Domingo et al. (2012)	15	19911	23	19911
Domingo et al. (2012)	5	22571	3	22571
Domingo et al. (2012)	6	19911	11	19911
Domingo et al. (2012)	4	22571	44	22571
Domingo et al. (2012)	20	19911	18	19911
Domingo et al. (2012)	2	22571	2	22571
Domingo et al. (2012)	14	19911	16	19911
Domingo et al. (2012)	22	22571	16	22571
Domingo et al. (2012)	53	19911	52	19911
Domingo et al. (2012)	3	22571	4	22571
Domingo et al. (2012)	9	19911	13	19911
Domingo et al. (2012)	16	22571	19	22571
Domingo et al. (2012)	0	19911	0	19911
Domingo et al. (2012)	6	22571	14	22571
Løkkeborg (1998)	5549	56700	4895	56700
Løkkeborg (1998)	5218	56700	4895	56700
Løkkeborg (2001)	7173	70200	5434	70200
Løkkeborg (2001)	6360	70200	5434	70200
Løkkeborg and Robertson (2002)	1935	58420	1572	58420
Løkkeborg and Robertson (2002)	1690	58420	1572	58420
Løkkeborg and Robertson (2002)	1775	58420	1572	58420
Løkkeborg and Robertson (2002)	2805	58420	2461	58420
Løkkeborg and Robertson (2002)	2712	58420	2461	58420
Løkkeborg and Robertson (2002)	2712	58420	2461	58420
Lydon and Starr (2005)	3	5318	4	4722
Lydon and Starr (2005)	19	5318	19	4722
Lydon and Starr (2005)	24	5318	26	4722
Lydon and Starr (2005)	1	5318	6	4722
Lydon and Starr (2005)	4	5318	3	4722
Lydon and Starr (2005)	2	5318	3	4722
Lydon and Starr (2005)	3	5318	3	4722
Lydon and Starr (2005)	1	5318	0	4722
Lydon and Starr (2005)	11	5318	13	4722
Lydon and Starr (2005)	6	5318	8	4722
Lydon and Starr (2005)	15	5318	18	4722
Lydon and Starr (2005)	0	5318	2	4722
Lydon and Starr (2005)	0	5318	1	4722
Lydon and Starr (2005)	0	5318	1	4722
Mancini et al. (2008)	6117	93855	6425	116415
Melvin et al. (2013)	458	16666	2119	73831
Melvin et al. (2014)	1197	90691	1104	78588
Robertson et al. (2006)	15221	158720	15364	158720
Robertson et al. (2006)	8825	119040	8904	179200

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